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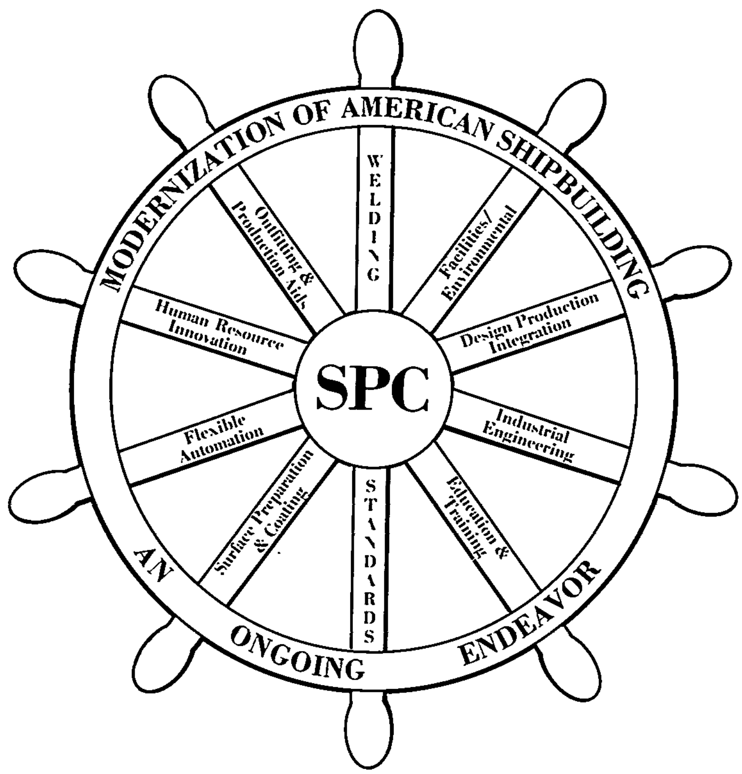

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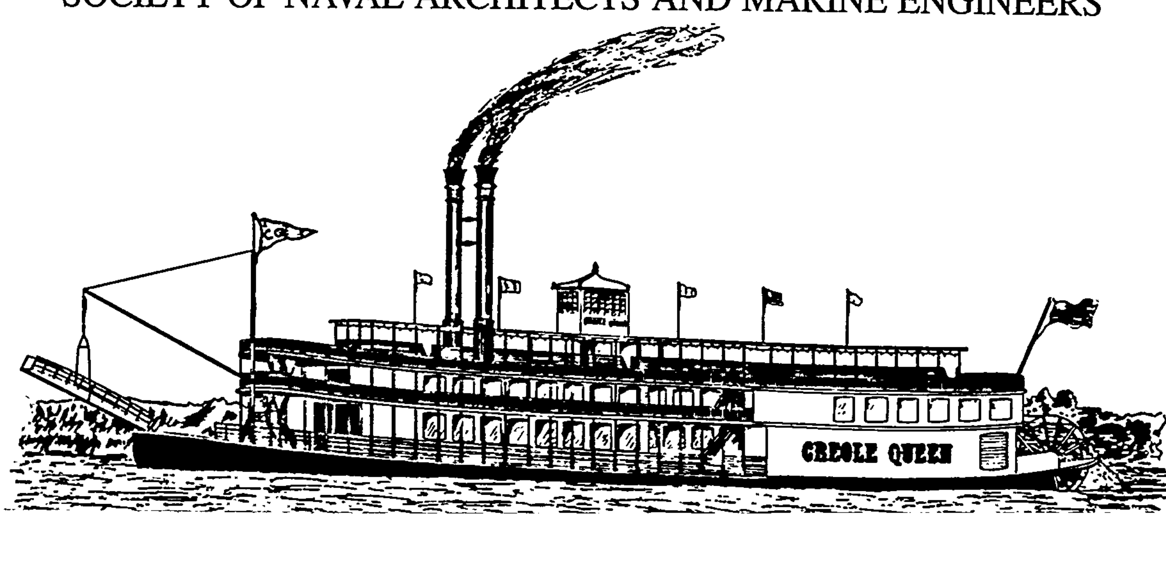

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Increased Duty Cycle for Plasma Arc Cutting Machines Through a Separated Automatic Plate Marking Station

No. 3

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ABSTRACT

Plate marking as currently practiced limits plasma arc cutting machine duty cycle. This in turn constrains plate fabrication process lane throughput. A separate automatic plate marking station which will significantly increase plasma arc cutting capacities is defined. A 60 to 100 percent increase in plate fabrication process lane throughput is anticipated while simultaneously reducing unit direct labor. The design is supported by technical feasibility demonstrations.

INTRODUCTION

This is the report of progress of a study nearing completion at Litton Systems, Inc. Ingalls Shipbuilding Division. Increased duty cycle for plasma arc cutting machines through a separated automatic plate marking station is the primary study objective. The underlying motivation for this objective is the expectation of reduced unit costs for finished plate parts cut by direct or computer numerically controlled plasma arc machines. A secondary study objective is improved geometric fidelity between the perimeter of cut plate parts and construction and reference lines interior to the parts. This improvement will help avoid the costs associated with correcting construction and reference line layout, and with compensating for construction errors caused by improperly located lines. Both of these objectives will result in reduced acquisition costs for new construction ships and ship overhauls. Both of these objectives move manufacture of ship structure in the direction of just in time support of building schedules based on erection of shop completed outfitting packages.

The study scope begins with analysis of plate fabrication process lane features common to United States shipbuilding industries. The study scope includes developing a design concept for an automatic plate marking system, showing technical feasibility, preparing preliminary designs and specifications, and identifying the system economic justification. Capitalization, development, and implementation of particular automatic plate marking systems based on the results of this study remains the option of individual shipyards.

For simplicity the automatic plate marking system described in this paper is herein after referred to as the AUTOMARK system.

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Design Concept Development Strategy

The study objectives arise from three rather straight forward observations apparently common to most shipyards. First, although the primary function of the plasma arc machines is to cut the outline separating parts from workpiece plate scrap, a significant portion of cutting table time and labor are associated with making marks. In a significant number of cases current marking practice fails to hold sufficient geometric fidelity with the part edge. This results in rework to correct the layout or to compensate for construction errors resulting from improperly located lines. Thirdly, alignment of plate with the plasma arc machines to assure that all of the required cuts lie entirely interior to the workpiece boundary is a tedious operation, often requiring multiple check passes with the machine and manual adjustment of plate position on the platen.

Variation in line position from the intended locations on the plate parts is attributed by the shipyard operating departments to several sources. These sources include movement of thin plate on the platen caused by the repeated

impacts of the marking tool and flexing of the out of plane waves characteristic of thin plate. A portion of each marking tool impact is reacted through the plasma arc cutting machine carriage. The impact reaction changes the relative alignment between the marking tool and the plasma torch. Welds joining plate parts into larger assemblages cause local shrinking. Local weld shrinking alters the position of construction and reference lines relative to the assemblage geometry.

The first two error sources will respond to modifications in the marking process and its position within the plate fabrication process lane. Line movement due to weld shrinking must be controlled by controlling weld sizes and sequences, establishing statistical norms for the shrinking that will occur, and compensating accordingly in the engineering data base.

The current practice of marking plate parts with a tool attached to the cutting tool carriage is evocative. This practice presumes a mechanically constant relationship between the marking tool and cutting tool coordinate systems. The distance and orientation from the marking tool center to the part edge generating region of the plasma torch are intended to remain fixed. In reality the situation is not quite so simple. The kerf edge varies from the torch centerline according to the direction of swirl and the direction of torch travel about the part perimeter.

Marking construction and reference lines on plate assemblages following weld joining of several parts into flat panels or curved shells is likewise evocative. Butt weld induced shrinking is accomplished prior to marking. This method requires two separate marking facilities; one for flat panels, and a second machine for curved shells. Each of these machines will be much larger, more complex, more costly, and therefore, exceedingly more difficult to economically justify than a single marking station prior to plate part joining. Additionally, unmarked plate parts must be fit for joining solely on the basis of geometric clues contained in adjacent edges of mating parts. Where part edges are curves or contain corners significantly differing from right angles, part edge based fitting is at best difficult. The likely result is an assemblage with margin geometry different from that intended.

The design concept development strategy includes the notion that automation need not mimic any prior manual or mechanized practice. Rather, it is necessary to accomplish the required properties of the production task being automated. Adjacent grouping of processes for local optimization purposes often creates productivity limits and masks opportunities available through other process combinations.

These factors taken together lead to a design concept development strategy comprised of the following elements. Develop an understanding of the properties of each task accomplished in the plate fabrication process lane, and of the bounds and constraints imposed by product requirements, production schedules and existing facility. Synthesize an exhaustive set of alternative plate fabrication process lane architectures after discarding those classes of process combination violating the bounds or constraints or otherwise obviously infeasible. Evaluate the remaining alternatives first as generalized task nodes and subsequently as embodying specific process technologies appropriate to each feasible architecture. Accomplish each of these evaluations structured against fixed criteria supporting the study objectives.

Each of the alternative system configurations is formed as a combination of three component considerations. These considerations are the choice of marking process, the choice of marking tool manipulation mechanism, and the choice of plate fabrication process lane architecture. The component considerations are very closely coupled. Each combination exhibits a unique property set. The properties of individual plate fabrication process lane architectures are evaluated separately to fathom infeasible and obviously impractical choices. The AUTOMARK system design concept is selected by evaluating the utility separately exhibited by discrete combinations of each candidate marking process with practical plate fabrication process lane architectures. Each combination anticipates embodiment with a class of marking tool manipulation mechanism particularly suited to the required process motion. The evaluations are accomplished against fixed criteria established to measure the capacity of alternative configurations to meet the system requirements and to achieve the system objectives.

The AUTOMARK system throughput capacity requirements are driven by anticipated plate fabrication shop loads through the next decade. The system should be capable of marking up to 12 maximum sized plates per hour.The maximum plate size is 720 inches by 156 inches. The minimum plate size is 72 inches by 56 inches. The anticipated mean plate size is 400 inches by 108 inches. The mark

density spectrum is typical for middle sized combatant ships.

SYSTEM OBJECTIVES

System Throughput

The prime objective of the AUTOMARK system is increased plate fabrication process lane productivity realized as increased count of plate workpieces put through the installed direct numerical controlled plate cutting resources per unit time. This is accomplished by using automated marking technologies and mark sensing technologies in a way that eliminates plate marking cycle time from cutting resource operation and drives plate alignment time toward irreducible minimum. The system should reduce direct labor content of the work accomplished.

Geometric Fidelity

An additional prime objective of the AUTOMARK system is consistent high levels of geometric fidelity of construction and reference lines to each other and to the part perimeter. The total mark position error budget is 0.04 inches from true position, anywhere on the workpiece plate surface, relative to the sensed coordinate axes for plasma arc cutting. This should result in a mark true position tolerance of less than 0.06 inches relative to the cut edges of parts. Alphanumeric character placement together with the equivalent bar code representation will be error free with respect to the information in the computer aided design data base.

Mark Characteristics

The secondary objective of the AUTOMARK system is generation of marks of high legibility, of enhanced mark utility, and permanence appropriate to use. The marks must be constituted compatible with the structural use of the plate. The marks must not degrade the metallurgical properties of the base material.

Marks physically changing the plate surface topology must not exceed 0.03 inches depth and must have sufficient width to assure primer flow into and bonding to all portions of the mark cavity. The mark cavity must approximate the rounded bottom cavity shape created by low stress impression die stamping.

All marks must survive 3 hours immersion in plasma coolant and 20 weeks outdoor stowage in a harsh marine industrial environment. Fiducial marks and construction and reference line marks must survive brush off abrasive blast cleaning and be legible through a touch up coat of 0.0015 inches thickness of primer. These marks must also survive mechanical primer removal for weld preparation.

Work Status Reporting

An additional secondary objective of the AUTOMARK system is automation of work accomplishment status reporting throughout the plate fabrication process lane. Reporting should begin during preparatory stacking of stock, and continue through to completion of part fabrication and marking.

System Requirements Sensitivity

The AUTOMARK system requirements are an essential parameter of this evaluation. The system requirements are also the measure of capability to perform the designated physical task.

It is important to note that changes to the system throughput requirements or to the mark performance requirements would likely introduce additional viable alternative plate fabrication process lane architectures. Additional viable marking technologies might also emerge. In particular, a stationary plate marking station might be viable. Productivity improvement as a result of separating automated plate marking from automated plate cutting does not seem sensitive to these kinds of requirement or embodiment changes.

PLATE FABRICATION PROCESS LANE COMPONENT OPERATIONS

Plate fabrication process lanes implemented in modern shipbuilding are similar in that the same operations are accomplished in the same sequence throughout the industry. Choice of plate fabrication process lane layout and the selection of equipment by a shipyard are strongly influenced by the history of the yard, its current business premise, and geographic and political constraints particular to the site. The model used in this analysis avoids reference to any given process lane. The separate operations in the process lane are considered in generic form in the feasible system architectures. The system properties of the generic operations functioning in these architectures and the consequent interrelationships thus established form the basis of this analysis.

Stock Stowage and Retrieval

Preparatory Stacking. Stock plate material is usually procured to meet the requirements of an entire ship or some very large assembly thereof. Even where specific plate sizes are ordered to match identified cutting nests, these plates are shipped in random order and often intermingled with mill run plate

of the same alloy and thickness. When the plate is received, it is stowed in racks or stacks according to some prearranged plan relating location to material type, size, and applicable contract. The utilization requirements for stock plate material are directly related to ship assembly schedules. These schedules seldom have any relation to the stowage locations. This results in a requirement to retrieve plate from widely scattered stowage locations. The widely separated location makes it difficult to support steady loading of plate onto the process lane input conveyor.

It is common practice to use a highly mobile crane to retrieve plates from stowage. The plates are landed on preparatory stacks within close reach of a crane dedicated to conveyor loading. Then plates are landed in reverse order of the intended daily utilization so that the first plate needed will be available first. Separate provision is made for landing plates required for emergent work adjacent to the conveyor loading crane.

Conveyor Loading. Conveyor loading characteristics are determined by the need to introduce varying sizes of plate into the blast cleaning station with uniform velocity and approximately uniform workpiece flow. To support uniform workpiece flow, the conveyor loading cycle time should not exceed the time for the shortest plate to advance its length through the blast cleaning station. Lifting of plate onto the conveyor from the preparatory or emergent work stacks is usually performed by a dedicated crane selected for plate handling characteristics, making numerous lifts of limited scope, and landing the plate in approximate alignment with the conveyor. The plate is mechanically aligned with the conveyor on an acorn table. The plate is then moved to the blast cleaning station on a rapid conveyor. The conveyor is comprised as a series of independently operable sections, permitting dynamic buffering internal to the conveyor of material flow into the blast cleaning station.

Blast Cleaning. The blast cleaning station is comprised as a series of machines dedicated to individual portions of this operation. Plate is handled through the machines on a conveyor. A rotary brush scours the plate surface of dirt and loosely adherent mill scale which otherwise dissipates the kinetic energy of the blast media. The brush also sweeps away any water which may have pooled on the plate surface. A blast cabinet impinges high velocity streams of blast media onto the plate to spall off tightly adherent oxides and other hard contaminants. Indentations left in the plate by impacting blast media generate an extended surface for bonding primer paints. Loose blast media is swept from the plate in a second brush machine. Finally the plate is cleaned of dusty residue in a vacuum cabinet.

Each of these machines accomplishes the action of a particular process with a constant intensity and in a static location corresponding to a small region on the plate. Process motion is derived from movement of the plate through the machines. To apply these processes uniformly, plate should progress through the blast cleaning station with a constant velocity. Wear rates are very high for blast cabinets operating unloaded. It is therefore necessary to achieve approximately uniform, near continuous workpiece flow through the blast cleaning station during operation.

Paint Application and Drying

Application of preconstruction primer to plate is accomplished by a series of two machines dedicated to the individual portions of this operation. Plate is handled through these machines on a conveyor. Spray paint application tools, usually on a linear reciprocator means with the reciprocation direction arranged transverse to plate motion, are mounted to spray the top and bottom of the plate. The process motion is a function of plate motion on the conveyor and manipulation of the application tools. The quantity of paint applied in a particular region of a plate is determined by a combination of plate motion, application tool manipulation, physical properties of the paint, and the specific atomization orifice installed in the application tools. Since these parameters are coupled, they cannot be independently varied without significantly affecting performance. Means are provided to limit the spread of paint over spray.

The paint drying tunnel is an enclosed volume with forced ventilation and elevated atmospheric temperature provided to flash the solvent from the applied coat. Means are provided as necessary for controlling release of this solvent to the environment. The time required to flash the paint solvent depends on the physical properties of the paint, mass flow of air, and the condition of air in the drying tunnel. The duration of travel through the drying tunnel is directly proportional to conveyor speed. Since these parameters are coupled, they cannot be independently varied without significantly affecting performance.

Direct Numerical Control Cutting

Each direct numerical control cutting station is comprised as a platen to hold workpieces and a servo gantry bridge and carriage arranged to manipulate the cutting tool over static workpieces. Each direct numerical control station is equipped with a controller which operates the machinery, drives the servo gantry bridge and carriage, and communicates with the computer aided design data base to receive tool trajectories. Direct numerical control cutting stations are usually equipped with pneumatic prick punch marking tools.These marking tools are capable of drawing dotted representations of lines and alphanumeric characters when supplied data in vector format. A cutting station may be equipped with a second carriage to permit simultaneous cutting of identical or mirror image parts. A cutting station may also be equipped with two platens situated endwise adjacent so that parts and scrap may be unloaded and workpieces loaded on one platen during marking and cutting operations on the other platen. Work may be accomplished using any thermal cutting process. Water shielded plasma cutting is the process usually implemented. This process is selected because it can achieve high tool rates at moderate cost.Where water shielded plasma cutting is implemented, provision must be made to flood the platen, muffling the plasma, recovering the shield water and quenching the kerf immediately following the region of working plasma.

Nest Breaking Platen

Parts remain nested with plate scrap after the part perimeters are cut. The great size and shape variety in shipbuilding plate parts require craftsmen working with mechanized lifting equipment to perform separation. Certain of the possible plate fabrication process lane architectures require handling a plate as a unit after parts cutting. For these architectures, tabs are left holding the parts and scrap as a stable structure. This structure is transferred to a dedicated platen for the final nest breaking. Craftsmen cut the tabs with manual torches and, working with mechanized lifting equipment, separate parts from scrap.

Marking Station

The marking station marks plate remotely from the direct numerical control cutting machines. This marking is accomplished in such a way that geometric registration is maintained between marks and corresponding cut plate parts. Marking remotely from the direct numerical control cutting machines reduces cycle time for these machines and increases workpiece throughput.

The marking station embodies marking devices, and appropriate marking device manipulation means, a controller to drive the equipment, and provision for handling plates through the station. Conveyor plate handling is provided through marking stations working on moving plate. Marking stations working static plate may incorporate a stationary platen. Marking stations may be partitioned according to the marking technology used to realize marks of a particular kind or intended use.

PLATE FABRICATION PROCESS LANE CONSTRAINTS

Work Capacity

Plate fabrication process lane work capacity or loading is considered in terms of workpiece plate completion rate, and the distributions of plate sizes, cutline lengths, and quantity of marks to be made. A constant work capacity is applied to all plate fabrication process lane architectures evaluated. This work capacity was developed in support of economic evaluation of automated plate marking systems, and is described elsewhere in this report.

Marking Station Process Motion

In those architectures which permit plate to remain stationary during marking operations, process motion derives entirely from manipulation of the marking device over the plate surface. Control of this manipulation requires compensation for lack of plate flatness and dynamic response of the plate under marking tool loads.

In those architectures which require plate motion during marking operations, process motion derives from both progress of the plate through the marking station and manipulation of the marking device over the plate surface. Control of this manipulation requires compensation for lack of plate flatness and dynamic response of the plate under marking tool loads. Conveying speed changes with plates of differing size and weight.

Material Flow Buffering or Queuing

Dynamic Buffering Between Conveyor Plate Loading and Blast Cleaning Station. Material is loaded onto the plate preparation line conveyor by piece. This loading method is essentially decoupled from any effect of plate size or weight. The result is highly varied lengths of plate are loaded at a relatively uniform rate.

Contrasting, blast cleaning operations are best performed at a uniform velocity on near continuous lengths of plate. Because the variable rate of plate length loading mismatches the loading requirements of the blast cleaning station, dynamic material flow buffering or queuing is necessary on the infeed conveyor.

Between Plate Preparation Line and Direct Numerical Control Cutting Machines. Material flow through the plate preparation line proceeds at a constant velocity based on process requirements of the constituent machines. The plate workpiece flow is directly related to the spectrum of plate lengths passing through the line at any given time. Contrasting, groups of plates are loaded onto the platens of a direct numerical control cutting machine nearly simultaneously. It is common to have plural cutting machines working in parallel. Work content and therefore the cutting machine cycle time are closely related to the character of the specific parts being cut. At best the cutting machine work content is loosely related to plate area. This results in a disparity of material flow on a plate workpiece basis between the plate preparation line and the cutting machines. This disparity in material flow requires buffering or queuing between the plate preparation line and direct numerical cutting machines.

Adjacent to Marking of Stationary Plate. In those architectures which permit plate to remain stationary during marking operations, rapid plate handling entering and exiting the marking station is necessary to provide time for accomplishing the required marks. A material flow buffer or queue is required immediately adjacent upstream to prevent plate exiting the prior operation from overtaking plate being marked. This buffer must have a capacity at least equivalent to the largest plate anticipated. An equivalent buffer is required immediately adjacent down stream to prevent rapid handling of plate exiting the marking station while preventing overtaking of plate entering the next operation. In certain architectures it is possible to to realize one of these material flow buffer or queue requirements with the static buffer between the plate preparation line and the cutting machines.

Material Handling Kinds

Automated Handling. Because of the weight involved, handling of plate and most plate parts is mechanized. Automated handling in the plate fabrication process lane with conveyors and vehicular conveyor extensions. Automated tray handling is possible but not used. Vertical and canted orientations of plate on conveyors are possible. These orientations exhibit some desirable properties but are not common because of procurement cost. Horizontally oriented plate conveyors are common. Progress along the conveyor is controlled by sensing plate position or the state of process completion on a particular plate workpiece.

Handling Requiring Manual Intervention. Crane handling on the plate fabrication process lane is accomplished with manually controlled cranes. Magnetic attachment is preferred over plate clamps except for handling small plate parts. This practice reduces handling distortion of the plate and eliminates a requirement for rigging personnel for most plate part lifts.

SYNTHESIS OF ALTERNATIVE PLATE FABRICATION PROCESS LANE ARCHITECTURES

An exhaustive set of alternate plate fabrication process lane architectures are synthesized for evaluation in development of the AUTOMARK system design concept. These architectures are shown on the accompanying diagrams, Figure 1.1 through Figure 1.5.

Bounds and Constraints

Synthesis of alternative plate fabrication process lane architectures is bounded by the fixed serial relationship between plate material stowage and retrieval, blast cleaning, preconstruction primer application, and part cutting. It is implicit that direct numerical control cutting machines receiving premarked plate must be provided with sensors to automate alignment with workpieces. It is also implicit that automated marking stations receiving precut plate must be provided with sensors to automate alignment with workpieces. Consequences of adding a marking station are considered for all possible positions on the process lane. Plate fabrication process lane throughput is currently constrained by the practice of marking with the cutting machines in series with cutting operations. Plate workpiece loading in excess of the present constraint is uniformly applied to all feasible alternatives.

Symbolic Notation

Symbolic notation of plate fabrication process lane component operations is used in diagrams to facilitate synthesis of alternative architectures.

Stock Stowage and Retrieval. Stock stowage and retrieval are considered as a single operation and noted as upper case letter S.

Blast Cleaning. All of the plate cleaning process machines are considered as constituent parts of the blast cleaning station and noted as upper case letter B.

Preconstruction Primer Application and Drying. Equipment applying and causing drying of the preconstruction primer coat on plate are considered as a single station and noted as upper case letter P.

Direct Numerical Control Cutting Machines. Each direct numerical control cutting machine is considered as a separate station and noted as upper case letter C.

Marking Station. The marking station is noted as upper case letter M. Where partitioning of the marking station is appropriate, the class of mark generated in each partition is identified by subscript. Line marking capability is identified by subscript lower case letter l as in M_l. Fiducial marking capability is identified by subscript lower case letter f as in M_f. Alphanumeric character marking capability is identified by subscript lower case letter a as in M_a. Bar code representation capability for part or cutting nest identifiers is identified by subscript lower case letter b as in M_b.

Nest Breaking Platen. Nest breaking platens, in the architectures requiring such, are separately noted as upper case letter N.

Material Handling. Material handling between positions on the plate fabrication process lane is noted as a line segment ——. Characteristics of particular moves are identified by subscript. Automated handling by conveyor, vehicular conveyor extension, or similar means is noted by subscript lower case letter c as in $—_c$. Material handling by crane or other means requiring manual intervention as noted by subscript lower case letter m as in $—_m$.

Material Flow Buffering. Material flow buffering or queuing is noted as upper case letter Q. Characteristics of particular buffers or queues are identified by subscript. Dynamic buffering accomplished on a conveyor or other automated handling means is identified by subscript lower case letter d as in Q_d. Buffering or queuing of material flow with plates unloaded from any handling means is termed static and is identified by subscript lower case letter s as in Q_s.

Compound Operations Within a Single Station. Conceivably marking may be compounded with the native operation of any station on the plate fabrication process lane. This compounding may be series, occurring sequentially in the same position, or parallel, occurring simultaneously. Series compounding is identified by a virgule / separating the operation symbols. Parallel compounding is identified by adjacent reverse virgules \\ separating the operation symbols.

EVALUATION OF CANDIDATE MARKING PROCESSES

The candidate marking processes are evaluated against fixed criteria established to exhibit properties relevant to operation in a plate fabrication process lane.

Marking Process Evaluation Criteria

Geometric Fidelity. Consistent high levels of geometric fidelity are essential in the generation of line and fiducial marks. Out of tolerance mark registration destroy the spatial relationship between a particular part and adjoining work. The rework created by this event is costly. Minimally, layout of the defective part must be manually accomplished. Maximally, the part or assembly of adjoining parts must be replaced. Geometric tolerances for line and fiducial marks are defined in section 3 of the system requirements.

Application Speed. Mark application speed of a particular process establishes the number of individual tools required to balance workpiece material flow in a given plate fabrication process lane. Marking process with higher inherent application speeds are more productive and tend to reduce the extent of manipulation equipment necessary. The minimum mark application speed performance is defined in section 5 of the system requirements.

System Envelope. Space is always a premium commodity within a shipyard fabrication shop. Shop floor space is presently valued approximately $50.00 per square foot. Plate conveyor systems cost in excess of $1000.00 per linear foot. In most shipyards, limited space is available for expansion of current fabrication shops. Excessive or undisciplined use of shop floor space could have far reaching detrimental effects on current productive facility and future automation projects. Allowable system envelope is defined in section 4 of the system requirements.

Legibility and Permanence of Applied Marks. Legibility and permanence of applied marks are measures of product suitability for the remaining plate fabrication process lane tasks and for the adjoining operations of assembly, erection and outfitting.

Necessary mark legibility and permanence are defined in section 3 of the system requirements.

Personnel Safety. Appropriate measures must be taken to control all health hazards posed by selected marking processes to personnel operating, maintaining, or observing the AUTOMARK system. Employers have a moral and a legal obligation to protect the safety of employees while at work. Highly complex and costly personnel safety measures increase the required system investment and potentially create task conflict. The personnel safety considerations appropriate to implementing the selected AUTOMARK system design concept are separately discussed below.

Surface Condition Impact. The surface condition of workpieces entering the marking station is established by prior processes. Marking process operating parameters and work quality may vary widely with changes in workpiece surface condition. Operating parameters and work quality of processes subsequent to marking may depend on receiving workpieces with surface conditions substantially unchanged from that delivered to the marking station. Performing marking modifies workpiece surface condition and may impact the legibility, permanence, or otherwise degrade the suitability of applied marks.

Equipment Cost. Capital equipment and system development costs for the AUTOMARK system are limited by the value of the anticipated productivity improvement. This permits recovery of the required investment in a reasonable period. Marking process related equipment and development costs are a major component of the required investment.

Operating and Maintenance Costs. The cost of operating and maintaining the present method of marking, as well as those for alternate methods is considered in the economic justification of an automated marking system.

Subordinate Criteria. Ease of marker manipulation, tool wear independence, and plate waviness impact were used as subordinate criteria in evaluating candidate marking processes.

Marking Process Evaluation Comments

Impression Stamping. Most large numerically controlled plate cutting machines in use today are equipped with automatic, pneumatic prick punch markers mounted on the torch carriage. Marking is accomplished prior to starting the cutting operation. Marking with a pneumatic prick punch offers a high degree of permanence and legibility. Equipment costs are relatively low. Marking and cutting coordinate frames are coincident. This practice also exhibits the following disadvantages.

Marking on the torch carriage accounts for a substantial amount of the total process time on the cutting platen. Shop observations revealed that approximately one third of the total alignment, marking, and cutting process time is spent marking. This reduces plasma arc duty cycle and results in constraining shop throughput as well. Thus the full cost savings attributed to installation of plasma arc machines cannot be realized.

Maintenance costs are high because of contact wear and tip breakage. An average of 5 percent of the observed total potential weekly hours per shift were lost as a direct result of maintenance required on the punch marker.

Punch marking on small thin plates (6 feet by 10 feet by 0.25 inches thick) produce observable plate motions which result in marking inaccuracies. In order to eliminate this, plates must be mechanically held in place.

The present form of punch marking is limited to a single tool. Because each must be separately drawn, the cycle time is far too great, punch marking cannot effectively generate alphanumeric characters.

Finally punch marking is extremely noisy.

The primary motivation for selecting a process lane architecture which moves the marking cycle away from the cutting machine is the potential for a significant increase in plasma arc duty cycle and shop throughput. Communication with suppliers of impression stamping devices has indicated that it is possible to manifold a great number of impression stamping tools together in fixed geometric relation to each other. With sufficient numbers of tools, adequate geometric resolution could be obtained. Approximately 2500 individually actuated punches would be necessary to accomplish the required marking. Process motion could be obtained from plate workpieces conveyed through the manifold tool. Alternatively, a smaller manifold tool could be manipulated over the workpiece surface. Several of the smaller resources would be necessary to accomplish the task since the impact marking mechanism is difficult to manipulate at high speeds because of its size and mass. Tool contact with moving plates will cause tool jerking and plate vibrations resulting in

degraded geometric resolution and excessive tool failure.

<u>Rotary Tool Engraving.</u> Rotary tool engraving, like impression stamping, offers a high degree of permanence and legibility for relatively low equipment costs. It also has a minimal impact on plate surfaces blast cleaned for preconstruction primer application. However, rotary engraving does have four inherent characteristics which limit its applicability for high speed plate marking.

Rotary tool engraving must be implemented with very high resolution surface tracking, tool force sensing, high speed manipulation means, in order to keep the engraving tool from impacting waves and other plate surface defects. Excessive contact force would result in tool breakage. Since rotary engraving tools operate at several thousand revolutions per minute, tool breakage could be very hazardous to workers in the area of the marking station.

Rotary tool engraving can engage the workpiece with a single tool from each manipulator. This requires separate drawing of each alphanumeric character and effectively limits rotary tool engraving to the generation of line marks.

Maintenance costs are high, both for the cost of replacement burrs and the labor for installation. Because of the anticipated high rate of tool breakage, a high level of disrupted production is also anticipated.

Finally rotary tool engraving is very noisy.

<u>Laser Engraving.</u> Laser marking is accomplished by focusing an intense, highly amplified beam of light on a target material. Minute amounts of the target material are vaporized by the beam, creating a round bottom cavity closely approximating low stress impression dye stamping. Width and depth of mark can be controlled by modifying the power output, rate of travel, and focal length of the beam delivery optic, and selection and control of the process cover gas. The marks are highly legible and have a high degree of permanence. Laser engraving does not degrade blast cleaned workpiece surfaces. High mark application speeds can be achieved. A single high power laser can provide power to multiple resources. Excess back shift laser power is available for other productive purposes such as laser thermal forming of plate parts. Lasers consume large amounts of power. Laser equipment costs are high. Safety considerations require conduct of laser marking inside a light tight enclosure equipped with interlock controls to assure personnel exclusion during operation.

<u>Ink Jet Printers.</u> Several types of programmable ink jet printers are available for noncontact marking of either single or multiple lines of information per pass. This is accomplished by projecting droplets of ink at high speed toward a workpiece surface while controlling the speed and direction of the droplets electrostatically.

The compactness and low mass of the ink jet printer make it very easy to manipulate. Additionally, the compactness of ink jet printing devices permit designing a plate marking station with a very small envelope. Printing with an ink jet on a blast cleaned or primed plate workpiece minimally degrades the suitability of the product for adjacent processes or operations. Ink jet maintenance consists generally of replacing orifices and replenishing ink supplies. Ink jet operation creates little noise.

Geometric resolution and legibility of ink jet marks will be degraded by the presence of waves in the plate workpieces. Ink jet marks made prior to preconstruction primer application will be occluded by the paint. Ink jet construction line marks made after preconstruction primer drying will be destroyed in preparation for welding adjoining structural components. Ink jet reference line marks made after preconstruction primer drying will be occluded by top coat painting of the assemblage.

<u>Zinc Oxide Powder Markers.</u> Zinc oxide powder markers use an oxy-fuel flame to preheat the workpiece surface so that a stream of metal powder melted by passing through the flame adheres to the workpiece as cast onto the surface. As the molten zinc cools, the unprotected mark surface oxidizes forming a characteristic gray white line approximately 0.03 inches wide. The nominal nozzle standoff from the workpiece is approximately 2 inches. The process is not highly sensitive to changes in standoff. This property relaxes the manipulation requirements for dynamic following workpiece contour with the marking tool. Zinc oxide powder marking tools have high moving mass. Mark application speeds of up to 800 inches per minute have been reported for zinc oxide powder markers. Since it is a material deposition process, the line width and geometric fidelity of zinc oxide powder marking vary considerably with application speed. Vendors recommend limiting application speed to between 175 and 225 inches per minute for consistent mark quality. The

limited application speed requires an increased number of marking tools to achieve the objective production level.

Water Jet Engraving. Water jet engraving marks by impinging a high speed stream with entrained abrasive onto the workpiece surface. The mark is created by abrasive cutting and by a compressive shearing at the point of impingement. The process is brittle and difficult to control in that minor changes in operating parameters result in moving from a surface material removing regime to deep cutting. The water used as a process fluid base promotes rapid oxidation of blast cleaned workpiece surfaces. Workpieces marked by water jet will require a second blast cleaning prior to preconstruction primer application. Passivation agents can be added to the process fluid to suppress oxidation. These add to operating cost of the marking system. Workpieces must still be dried and abrasive swarf removed prior to preconstruction primer application.

EVALUATION OF MARKING TOOL MANIPULATION MECHANISMS

Manipulation mechanisms are not evaluated separately since the required process motion varies with each combination of marking process and plate fabrication process lane architecture. For those architectures which permit stationary workpieces during marking, articulated arms, dynamic bridge and carriage, static manifold tool and dynamic bridge , and combinations of these mechanisms are considered. For those architectures which require workpiece motion during marking, articulated arms, dynamic bridge and carriage, dynamic carriage on static bridge, and static manifold tool on static bridge mechanisms are considered. Combinations of these mechanisms are also considered.

The evaluation first considered the suitability, and kinetic and mechanical feasibility of a particular mechanism class for manipulation of marking tools in a combination of marking process and plate fabrication process lane architecture . Second, mechanical and control complexities are considered. This includes the scale of manipulation required, the size and mass of the necessary links, difficulty of mechanical design, extent of moving mass and coupled inertia effects, and the difficultly of achieving the required positional resolution. A determination of utility differentiated between candidate mechanisms on the basis of simplicity, robustness, achievement of required process motion, and probable cost.

EVALUATION OF PLATE FABRICATION PROCESS LANE ARCHITECTURES

Infeasible Architectures

The marking processes considered in this evaluation mark a workpiece by local deposition of material in the surface or locally ordered changes in the contour on the surface. Blast cleaning spalls off tightly adherent oxides generating a new surface of randomly positioned and oriented facets. Marks made prior to blast cleaning reside on or in the oxides being removed and are destroyed as a result of the operation. Marks made simultaneously or in parallel with blast cleaning are likewise destroyed. Architectures 1 ,2 ,3 ,4 and 5 mark before blast cleaning. Architecture 6 marks in parallel with blast cleaning. All of these architectures are infeasible.

Blast cleaning and preconstruction primer application and drying acquire a component of process motion from progress of the plate workpieces through the operation station. A series or sequential combination of such processes into a single station with a moving plate marking process into a single station is a physical impossibility since plate remains in the station only long enough to complete the first of the combined processes. This is a degenerate form of architectures comprised as a series of moving plate stations. Architecture 7 is a series combination of blast cleaning and moving plate marking. Architecture 11 is a series combination of preconstruction primer application and drying moving plate marking. Both of these architectures are infeasible.

Architecture 10 is a parallel or simultaneous combination of moving plate marking and preconstruction primer application and drying. Marks generated by material deposition processes are occluded by applied paint. Metal removal marking processes create locally high temperatures which may serve as an ignition source for paint solvents. Impression marking equipment includes many moving parts with small clearances and high bearing loads. Impression marking equipment operating in a single station with preconstruction primer application would be quickly destroyed by abrasive action of paint pigment or seized by binding with paint vehicle residues. Architecture 10 is infeasible.

Parallel or simultaneous operation of marking and thermal cutting of plate as in architecture 19 might be realized in several conceivable ways. First, marking equipment might be manipulated over the workpiece surface by an articulated mechanism mounted in the

cutting machine bridge but working independently of the torch carriage. The articulated mechanism would be occluded from operation on the side of the cutting machine bridge opposite the articulated mechanism mounting. The course of marking trajectories is independent from the course of cutting line trajectories. The lengths if both trajectory classes are generally of the same order of magnitude. Simultaneous operation of both processes and completion in the same time frame requires a marking tool manipulator reach of at least half the diagonal of the largest plate anticipated. The manipulator must have a tool point operating speed in excess of torch speed and tool point positional accuracy better than 0.0315 inches. These requirements exceed the state of art in both mechanical design and positional control.

The second alternative is an independent marking bridge with retractable marking tools such that the cutting bridge may pass through. Tool velocity along the marking trajectories must be greater than along cut line trajectories to compensate for not marking during cutting bridge pass through periods. Height to allow clear passage of the cutting bridge requires mounting the marking tools on a telescoping mechanism. The marking tools are then cantilevered approximately 10 feet to the bearing support mounted on the cutting machine bridge. The required positional accuracy of marking is 0.0315 inches. These requirements are near the leading edge of art in mechanical design.

A third alternative is an independent marking bridge not able to pass the cutting bridge. After a short period one of the bridges would often preclude the other from most work opportunities. In this case, operation reverts to the series equivalent architecture.

The final alternative is an endwise dual position cutting platen. Each position of the platen is provided with an independent bridge not capable of passing. Both bridges are equipped to accomplish marking and cutting. Both bridges could accomplish work on either end. Since cutting trajectories should be continuous, one bridge would often preclude the other from most work opportunities. Handling plate on the platen and picking out cut parts and scrap occupies a major portion of cutting time. Thus marking speeds must be much higher than cutting speeds. These speeds are not supported by the state of art in marking. Working the bridges separately is the equivalent of doubling the number of serial marking and cutting machines. Architecture 19 is infeasible.

In architectures 20, 27, 28, and 29 marking is combined sequentially or in series with breaking of the nest and separation of parts and scrap. Tabs connecting the parts to the nest skeleton remain after cutting to facilitate handling. Nest breaking and parts separation are inherently manual operations and require a stationary workpiece. In these architectures marking is realized as a stationary workpiece operation. Plate workpiece cycle time for series combined marking and nest breaking is at least on the order of plate workpiece cycle time for part cutting . This excessive plate workpiece cycle time in a single station constrains throughput for the plate fabrication process lane. Architectures 20, 27, 28, and 29 fail the system prime objective and are infeasible.

Marking is combined simultaneously or in parallel with breaking of the nest and separation of parts and scrap in architectures 21, 24, 25, and 26. Economically feasible automated marking requires apriori fixed part location and orientation internal to a particular plate workpiece. Nest breaking and parts separation destroys this relation. Automated part marking is incompatible in parallel combination with nest breaking and parts separation. Workpiece cycle time for manual parts marking far exceeds the workpiece cycle time for part cutting. This excessive plate workpiece cycle time in a single station constrains the plate fabrication process lane throughput. Architectures 21, 24, 25, and 26 fail the system prime objective and are infeasible.

Architectures 34, 35, 36, 37, 38, 39, and 40 implement nest breaking and separation of parts and scrap prior to part marking. Automated part marking requires apriori knowledge of part identity, location, and orientation. Automation to preserve this knowledge for loose parts is economically infeasible. Manual parts identification, positioning and orientation for automated marking add sufficient plate workpiece cycle time to this station to constrain plate fabrication process lane throughput. Manual layout and marking of loose parts requires additional plate workpiece cycle time. Architectures 34, 35, 36, 37, 38, 39 and 40 fail the system prime objective and are infeasible.

Feasible Architectures

Practicality. Independent of the marking technology implemented, it is evident that the feasible plate fabrication process lane architectures exhibit varying degrees of practicality. The system objectives anticipate economic gain realized through productivity enhancement. Criteria used

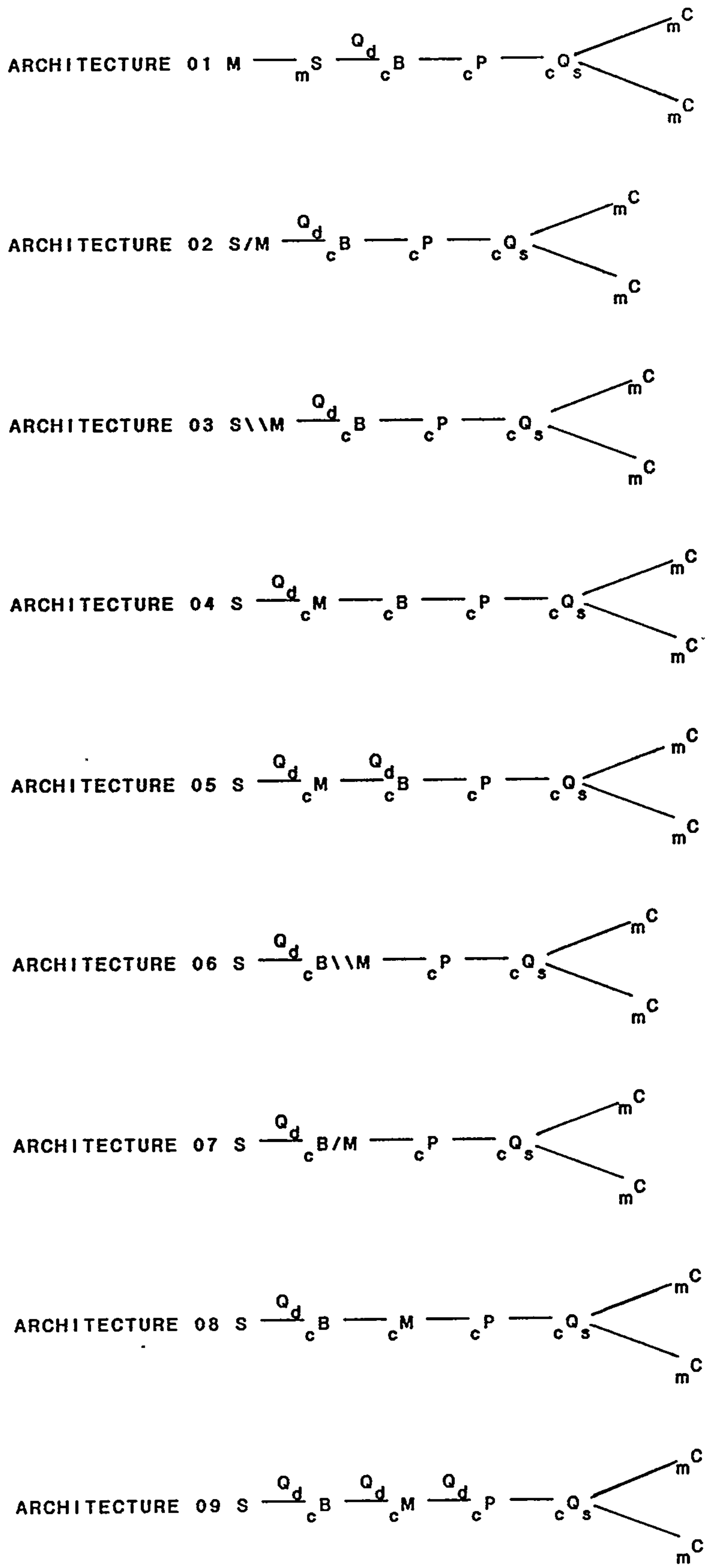

Figure 1.1. ALTERNATIVE PLATE FABRICATION PROCESS LANE ARCHITECTURES

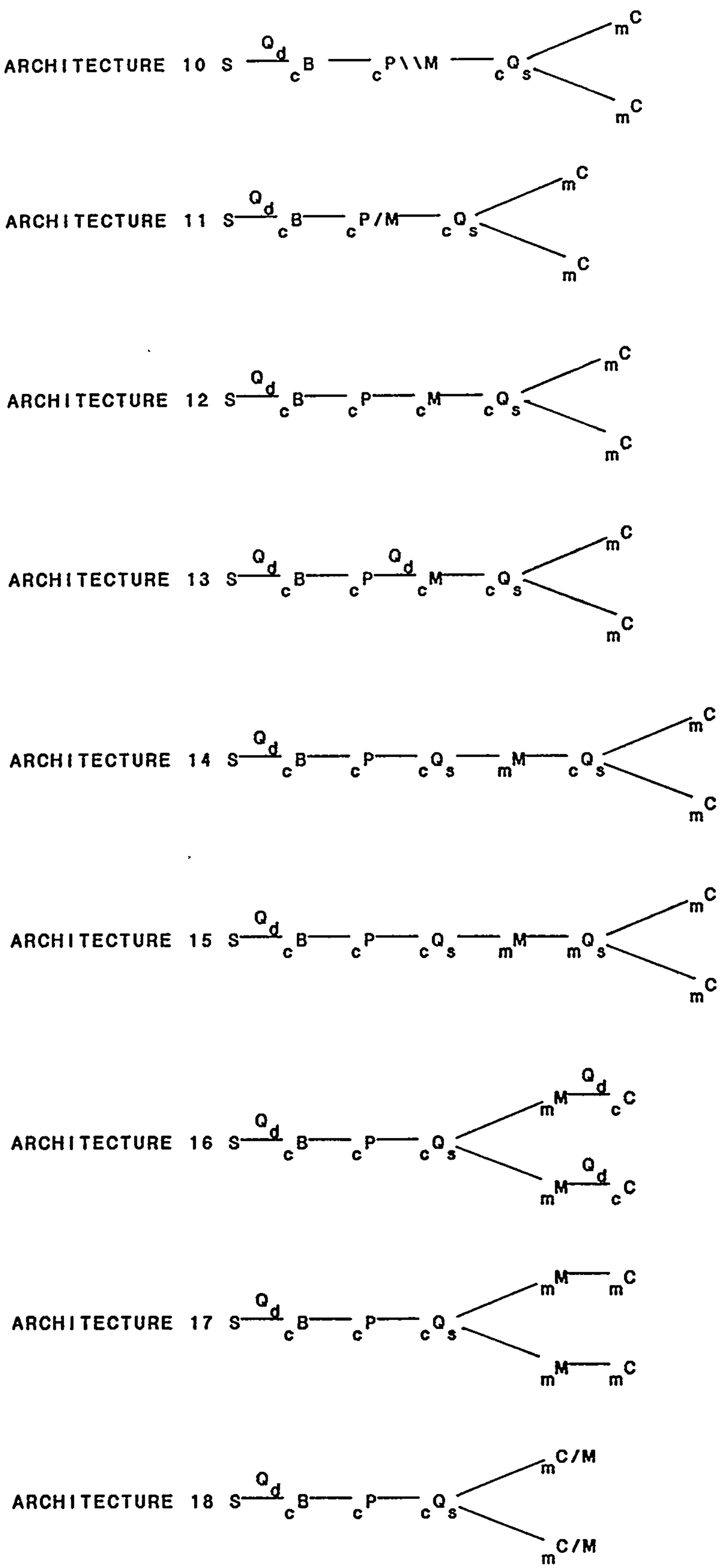

Figure 1.2. ALTERNATIVE PLATE FABRICATION PROCESS LANE ARCHITECTURES

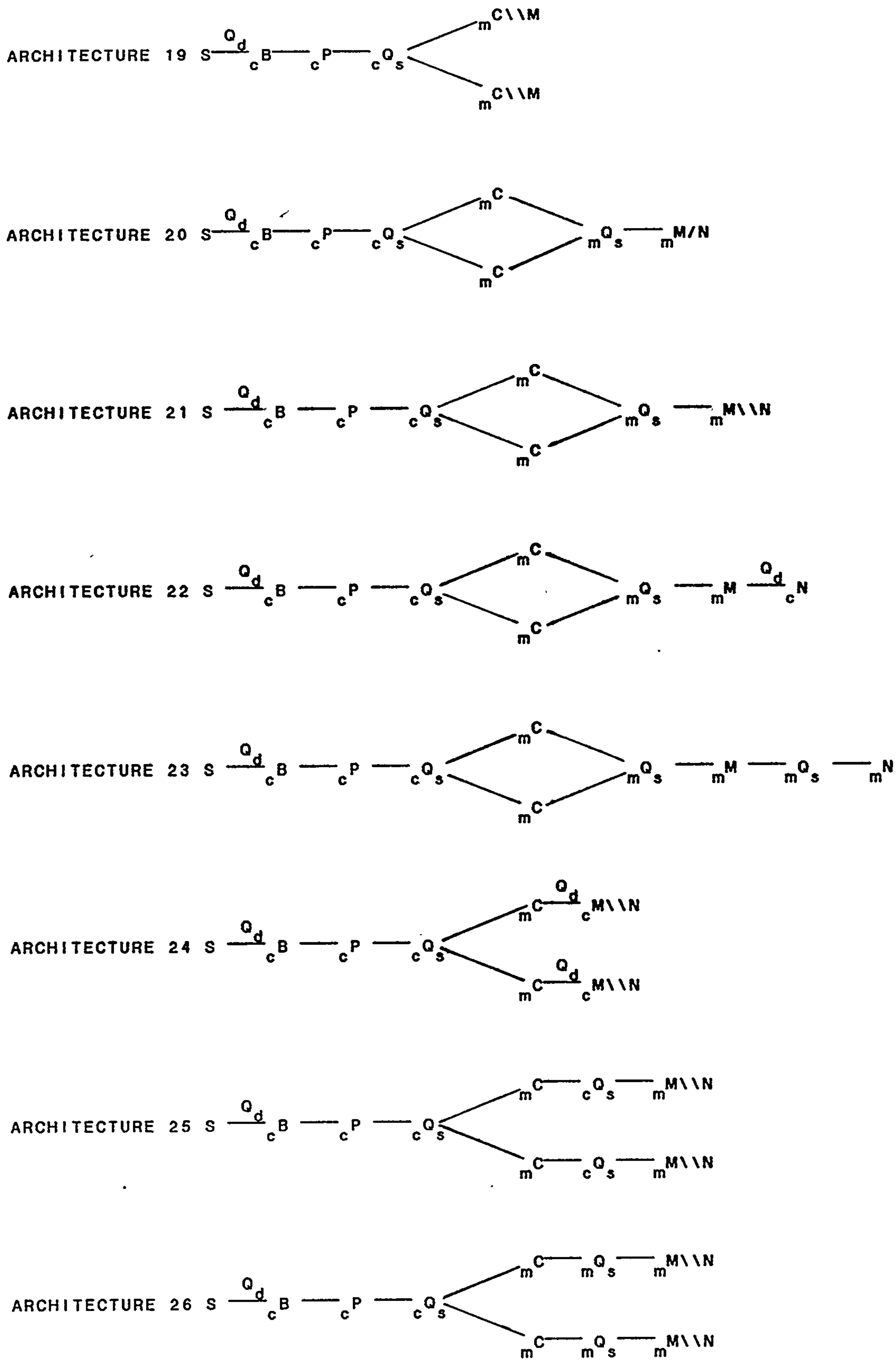

Figure 1.3. ALTERNATIVE PLATE FABRICATION PROCESS LANE ARCHITECTURES

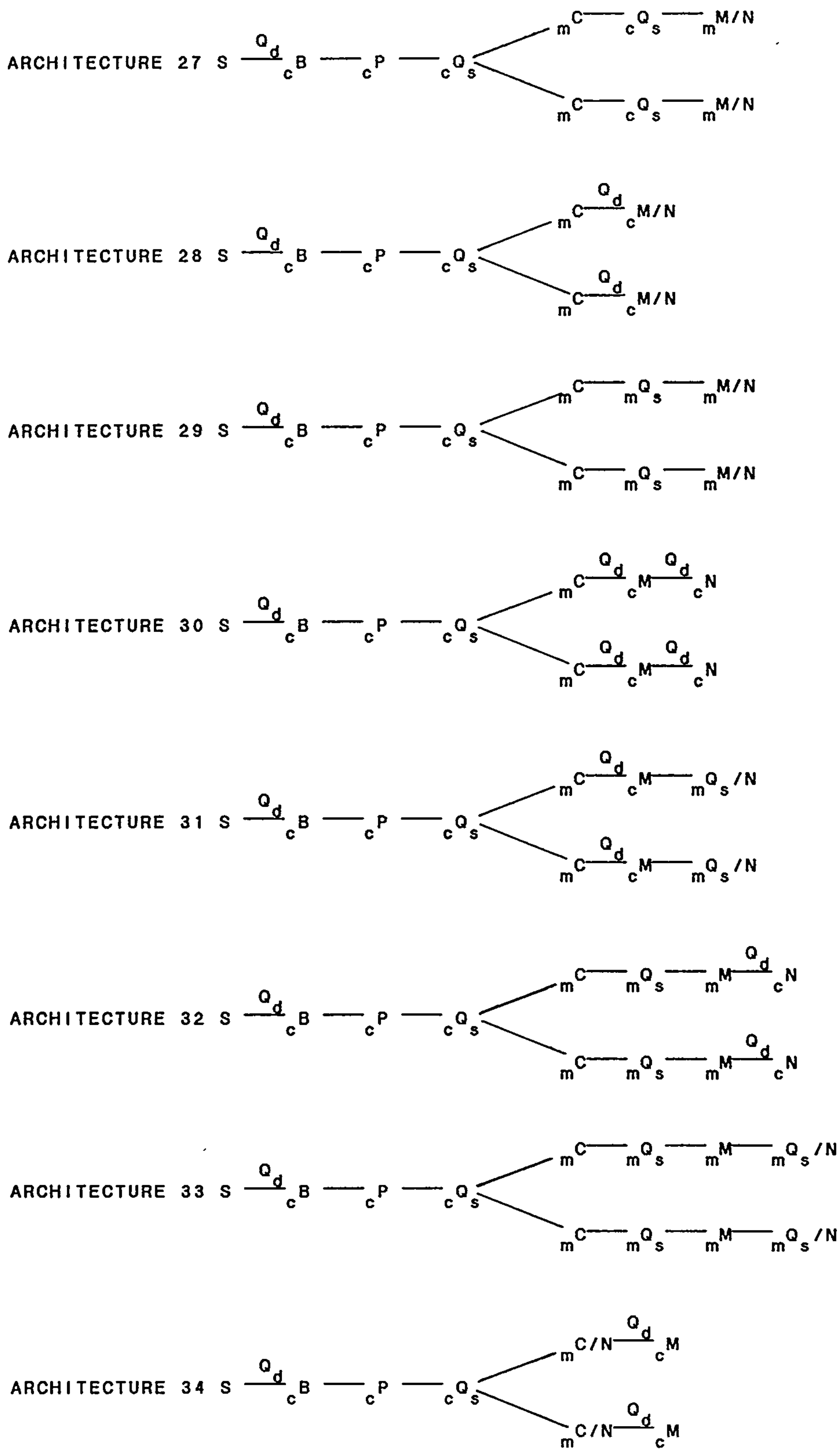

Figure 1.4. ALTERNATIVE PLATE FABRICATION PROCESS LANE ARCHITECTURES

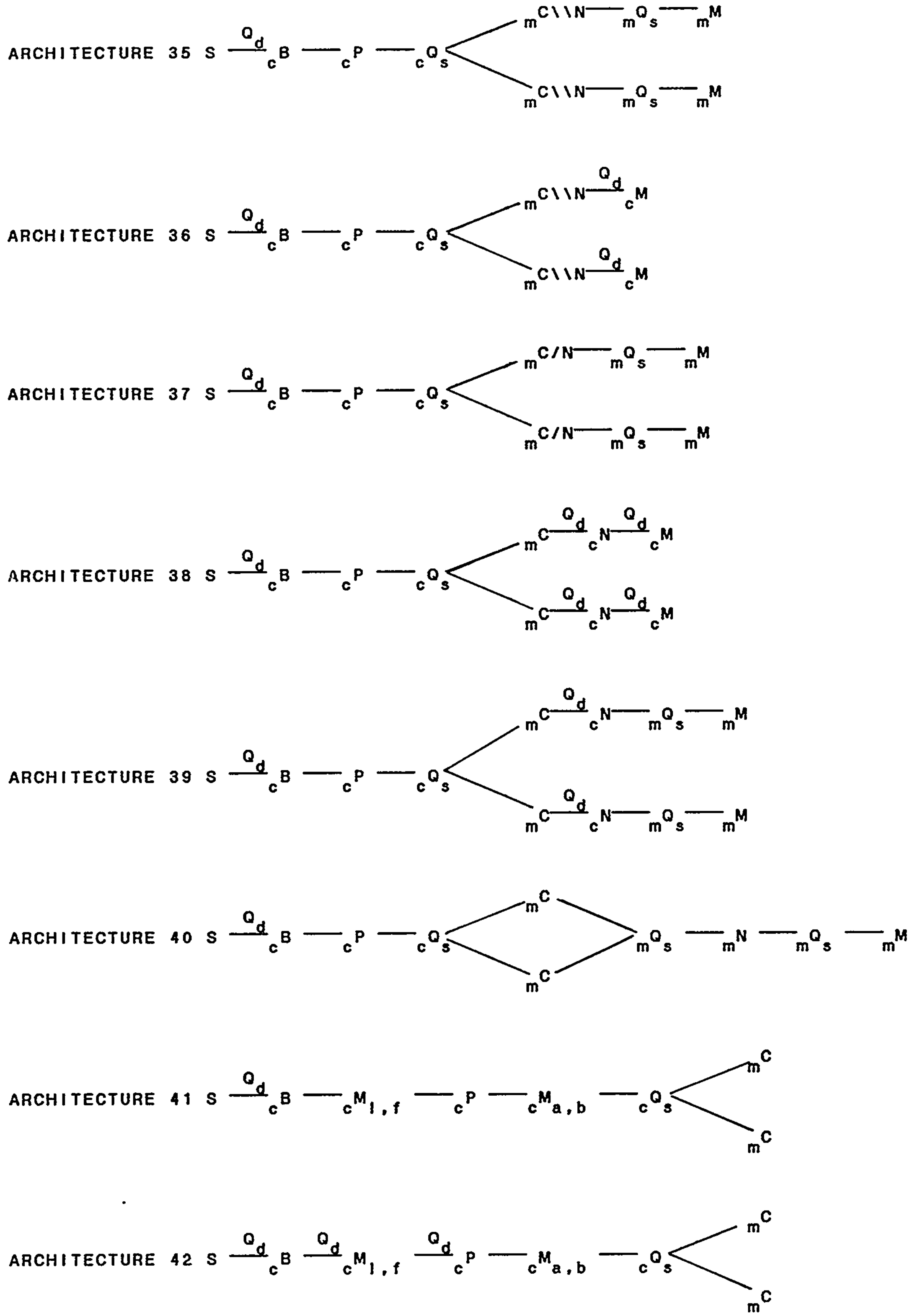

Figure 1.5. ALTERNATIVE PLATE FABRICATION PROCESS LANE ARCHITECTURES

to evaluate practicality derive from economic considerations.

Practicality Evaluation Criteria. There is a strong correspondence between the floor area occupied by a process lane and the topology of the process lane architecture. Architectures with numerous stations or complex material handling paths occupy larger areas. The manufacturing floor of most shipyards is largely populated with existing facility. If implementation of a manufacturing system within the process lane requires expansion of the floor under roof or relocation of existing productive facility, the related costs are often comparable with the acquisition costs of the new equipment occupying the area. Architectures occupying less manufacturing floor area are more practical.

In an economically driven environment the cost of equipment is a significant measure of manufacturing system practicality.Each architecture is directed toward achieving the same level of productivity enhancement. The less costly is the more practical. Cost is roughly related to the product of the amount of equipment required and the necessary mechanical complexity. Development and the necessary controller complexity also affect equipment cost but are strongly influenced by the selection of specific processes for implementation.

Dynamic material flow buffers, parallel process stations and additional bridge cranes or other material handling devices increase the amount of equipment required to accomplish a particular functionality. Adding degrees of freedom to the marking tool manipulator, or conveyor platens to the direct numerical controlled plate cutting machines increases mechanical complexity. Apart from a contribution to acquisition cost, increased mechanical complexity introduces added risk of development difficulties and tends to further reduce practicality.

The extent of touch labor required in plate fabrication is an inherent property of these architectures. The controllable touch labor content is mostly related to material handling requiring manual intervention and to nest breaking. Touch labor related to marking is controllable only in those architectures accomplishing this operation after part cutting. Reduction of the touch labor content of plate fabrication is a system objective. Increased touch labor content as a consequence of plate fabrication process lane architecture reduces practicality.

The probability of task conflict, competition between workpieces for the same resource or between resources for the same workpiece is particular to the topology of each architecture. The conflict arises from an imbalance of work rates in the component stations of the process lane. Extremely wide variation in work content exists between individual plate workpieces; particularly for plate marking and for plate cutting. The affect of this imbalance may be reduced by careful routing of workpieces through parallel resources. Craftsmen are essential to some links of these architectures, but add to task conflict by performance variability not accounted for in the route planning model. Task conflict tends to multiply the touch labor requirement of work accomplishment. Increased task conflict decreases practicality.

It is reasonably assumed that the reliability of a component resource can be made relatively constant and independent of position within the process lane architecture. The affect of failure of a component resource can vary widely with position in process lane architecture. In the case of the otherwise practical architectures considered in this study, however, the affect of marking resource reliability is not discriminating.

Each of the criteria are considered to weigh equally in the evaluation. A high level of impracticality under a single criterion is sufficient to determine a plate fabrication process lane impractical. In support of the determination the table also shows the contributions under subordinate criteria to the overall properties of the feasible plate fabrication process lane architectures. The following comments identify particular reasons for finding certain of the architectures impractical.

Practicality Evaluation Comments. Architectures 9 and 13 are similar. Both mark stationary workpieces in the plate preparation line portion of the process lane. Workpieces are handled into and out the marking station on the plate preparation line conveyor. Dynamic buffering isolates the marking station from other plate preparation stations. Architecture 42 is related to architectures 9 and 13. The marking resource is partitioned to accomplish line and fiducial marking prior to preconstruction primer application. Alphanumeric marking and generation of bar code representations of nest and part identifiers are accomplished following preconstruction primer drying. The time spacing of workpieces on the plate preparation line taxes the available speed of current marking technologies for completing the required marks on a nominal plate cutting nest.

The time required to handle plate into and out of the marking station reduces the time available for completing plate marking before impacting preparation line operation. Many workpieces are significantly different from the nominal plate cutting nest. Existence of these different from nominal plates creates task conflict that results in unacceptable delays in preparation line operation. Resolution requires impractical numbers of marking tools.

The time spacing for cutting plate is different and often greater than the intervals between stations on the plate preparation line. Positioning a marking resource between the preparation line and the cutting machines reduces the burden of mark generation speed and the production sensitivity to the amount of marking per plate associated with marking of stationary plate. This requires isolation of the marking station from the plate preparation line with a static buffer or queue. In architecture 14 plate workpieces are crane lifted from the queue to the marking platen and handled out the marking station on a conveyor and into a second queue to await cutting. In architecture 15 plate workpieces are crane lifted from the queue to the marking platen and crane lifted from the marking platen to a second queue to await cutting. The additional crane handling implemented in these architectures requires acquisition of an additional crane to accomplish marking station workpiece handling and a portion of the cutting machine loading tasks. Operation of two cranes in the same queue implies at least a medium level of task conflict. Architecture 16 implements parallel marking stations crane loaded from the queue at the end of the plate preparation line. Each of the marking stations is coupled to a single cutting machine with a conveyor equipped for dynamic buffering. This topology provides additional workpiece time available for marking. Mismatch between marking time and cutting time for separate plates still exists and implies at least a medium level of task conflict. These architectures require high to very high envelope. These architectures require high to very high equipment cost. Knowledge of plate size, thickness, and alloy is created as individual stock pieces are retrieved from storage and loaded onto the plate fabrication process lane infeed conveyor. Preservation of this data is essential to automatic correlation of material with marking and cutting information. While plate remains on the fabrication process lane infeed conveyor the identity of each workpiece is intact. When plate is removed from the conveyor to the queue, workpiece identity is destroyed. Craftsmen determine the need to load plate from the queue to the marking station. It is not possible to guarantee a specific order of plate removal from the queue. Functioning of these architectures requires manually maintained identity by some means equivalent to application of bar coded labels to each workpiece entering the queue. Otherwise the information must be recreated during loading of the marking station. Architectures 14, 15 and 16 are impractical.

Most shipyards currently mark plate in series combination with cutting. Plate is crane lifted onto the platen and manually aligned with the cutting machine axes. After the cutting machine operator sets the datum to the plate edges, a pneumatic prick punch mounted in the torch carriage automatically marks construction and reference lines. Direct numerical control plate cutting machines are usually equipped to generate the alphanumeric characters necessary for part identification. This capability is seldom used because the large cycle time required constrains plate workpiece throughput. It is common practice for the cutting machine operator or a layout man to manually identify parts in parallel with the line marking operation. This practice is potentially dangerous and is subject to error. Architecture 18 achieves the objective throughput increase by at least doubling the number of direct numerical controlled cutting machines currently installed in the plate fabrication process lane. Several factors combine to establish the impracticality of this architecture. The number of additional plate cutting machines required have a very large envelope and a very high acquisition cost. Because of the length of traverse involved a second crane is required . This architecture does nothing to reduce the manual labor content of plate fabrication. Knowledge of workpiece size, thickness, and alloy must be recreated during cutting machine loading. The cutting nest assignment of the plate must then be identified. Finally, two cranes servicing several plate cutting machines from a single queue implies a high level of task conflict. Architecture 18 is impractical.

The architectures that accomplish marking after plate part cutting form two related topological groups. Architectures 22 and 23 complete plate part fabrication in a single line of operation stations. Workpiece handling arrangements differentiate between these architectures. Architectures 30, 31, 32 and 33 complete plate part fabrication in parallel lines of operation stations. Workpiece handling arrangements differentiate between these architectures. All members of both

groups require very high envelopes and involve very high acquisition costs. All have a high touch labor content and involve a very high level if task conflict as inherent properties of the architecture. Architectures 22, 23, 30, 31, 32 and 33 are impractical.

Combined Utility. The AUTOMARK design concept is selected by evaluating the utility separately exhibited discrete combinations of each candidate marking process with practical plate fabrication process lane architectures. Each combination anticipates embodiment with a class of manipulation mechanism particularly suited to the required process motion. The number of marking tools implemented in each is variable and specific to each combination. Adequacy of each combination to meet the plate fabrication process lane throughput improvement is assumed. The evaluation considers the coupled properties of each combination. Utility is evaluated according to the properties of each combination measured against fixed criteria. These criteria express the suitability of the product for assembly and other subsequent shipyard operations, marking tool manipulation factors influencing the magnitude of required investment, the magnitude of operating costs, and the means necessary to assure personnel safety. In support of the determination the properties of each combination are also examined against subordinate criteria.

Combined Utility Evaluation Criteria. It is essential that the product of the plate fabrication process lane exhibit a consistent high level of geometric fidelity and mark legibility. Line marks must withstand assembly and erection operations. Identification marks must maintain legibility at least through first level assembly. The parts will be stored outdoors in a harsh marine environment. Degradation of the required mark legibility or permanence by or as the result of factors associated with adjacent processes reduces suitability.

Separate classes of mechanism are more suitable than others for the manipulation of each candidate marking processes in a given position within the plate fabrication process lane architecture. The mechanism class and the moving mass anticipated with each embodiment reflect the mechanical complexity associated with the combinations. These factors together with closing of the manipulation kinematic chain by workpiece contact marking processes are reflected in the combination control complexity. The number of marking tools required multiply the complexity. All of these factors contribute to increased capitol investment requirement. In an economically driven environment, other factors being equal, reduced investment requirements increase utility.

Operating costs include power and expendables, and the costs associated with reliability and maintainability considerations. These factors directly influence utility in terms of return on investment. Power, expendables, and maintenance labor and supplies appear as pure costs. System down time appears as production opportunities lost and disruption to adjacent processes and operations.

Personnel safety must be assured without compromise. The complexity of assuring personnel safety is specific to each combination of marking process, manipulation mechanism, and position in the plate fabrication process lane. Greater safety assurance complexity is reflected in greater required investment and reduced utility.

Combined Utility Evaluation Comments. The most influential factors in determining utility for practical plate fabrication process lane architectures coupled to particular marking process and suitable manipulation mechanisms are the effects of adjacent processes on the suitability for purpose of the resulting cut and marked plate parts. These factors establish the unacceptability of water jet engraving and zinc oxide powder marking. Ink jet marking is unacceptable in architecture 8 because preconstruction primer application occludes the marks. Ink jet marking is unacceptable for lines but good for alphanumeric characters and bar code representations of cutting nest and part identifiers in architectures 12 and 17. Impression stamping before and after preconstruction primer application if the number of impressions is reduced and the the impression impulse and marking tool dimensions are carefully controlled so that damage to the preconstruction primer is limited. The very great mechanical complexity of impression stamping equipment necessary for this application will create an unacceptable reliability and maintainability problem. Rotary tool engraving will exhibit a similar reliability problem. Very high levels of tool breakage and out of specification marking cuts are anticipated because of the difficulties of high speed force and position controlled manipulation over waves and other imperfections in the plate workpiece surface which cannot be well known apriori. The best balance of product suitability is obtained by partitioning the marking resource as in architecture 41, and selecting laser engraving for lines and fiducial marks, and ink jet marking for alphanumeric characters and bar code representations

of cutting nest and part identifiers. This choice is substantiated by the marking tool manipulation factors, and by the the operating factors. The complexity of assuring personnel safety is acceptable and not significantly different than in the other architectures.

DESIGN CONCEPT DETERMINATION

The design concept selected for the AUTOMARK system partitions the workpiece marking task into 2 separated marking stations. The partition is made because of differing marking tool requirements for lines and for alphanumeric character marks. The partition is also made because of differing permanence requirements for lines and for alphanumeric character marks. Lines and fiducial marks are laser engraved on moving plate workpieces prior to preconstruction primer application. Alphanumeric characters and bar code representations of cutting nest and part identifiers are ink jet marked on moving plate workpieces following preconstruction primer drying. The direct numerical control cutting machines are provided with machine vision sensors to automate alignment of the plasma arc torch trajectories with workpieces on the platen.

Figure 2, is a schematic representation of the design concept selected for the AUTOMARK system. It illustrates process accomplishment and shows information flow through the system.

Beginning with the daily or the weekly cutting plan, a requirement for specific stock plates is generated. This requirement is transmitted an item at a time to the plate stock stowage yard. There the identity and location of the required plate are displayed for the conveyor loading personnel. As each workpiece plate is loaded onto the conveyor and confirmed, its association with a particular cutting nest is created. The shipyard material data system is advised. The next stock plate requirement is then displayed and the conveyor loading operation repeated.

The mechanical sequencing preserves the nest association of the workpieces. The corresponding line and alphanumeric character data is accessed. Fiducial mark locations are generated and added to the nest. After data parsing, marking tool trajectories are planned for the line marking station and the alphanumeric character marking station. Operation of the line marking station and operation of the alphanumeric character marking station creates the marks planned for each particular workpiece plate. Workpiece plates are automatically unloaded from the preparation line conveyor into a static queue following marking completion.

Plates are lifted from the static queue and landed onto the direct numerical control cutting machine platens. Automated alignment begins with the direct numerical control cutting machine bridge and carriage positioned such that the machine vision camera images the corner of the workpiece opposite the lead in cut. Plate size data is accessed through the cutting nest identifier marked on the plate. Using this data as apriori guidance information, and edge location data from the machine vision camera as feedback, the AUTOMARK system traces the workpiece plate boundaries counterclockwise to the lead in cut. The fiducial marks along these boundaries are made in positions related to plate size. The fiducial marks serve as the coordinate reference for the line marks on the workpiece. When the machine vision identifies a fiducial mark, the location of the fiducial mark in camera coordinates is associated with the current camera location in cutting machine coordinates. The relation between the workpiece coordinate reference and the direct numerical control cutting machine coordinate reference is computed using the sensed locations of the fiducial marks. The cutting trajectories are then translated and rotated according to the result and the plasma arc torch operation initiated.

TECHNICAL FEASIBILITY DEMONSTRATIONS

Technical feasibility demonstrations were accomplished to establish reasonable assurance that the AUTOMARK system can be successfully developed and that the system performance will meet the study objectives. These demonstrations concentrate on the making of line and fiducial marks and the sensing of fiducial marks for automatic alignment with the cut trajectories. Because the required speeds and geometric fidelity requirements thoroughly tax the state of available technology, these tasks are considered more difficult than ink jet application of alphanumeric characters and the bar code representations of these characters.

The demonstrations show that it is possible to laser engrave marks meeting the system requirements. They show that it is possible to construct a control device to place these marks anywhere on the largest plate and in any direction required. The demonstrations further show that sufficient data exists in the nest images as currently formatted to programmatically place fiducial marks in the nest image, to parse the data, and assign marking duty among the several line marking subresources, and to

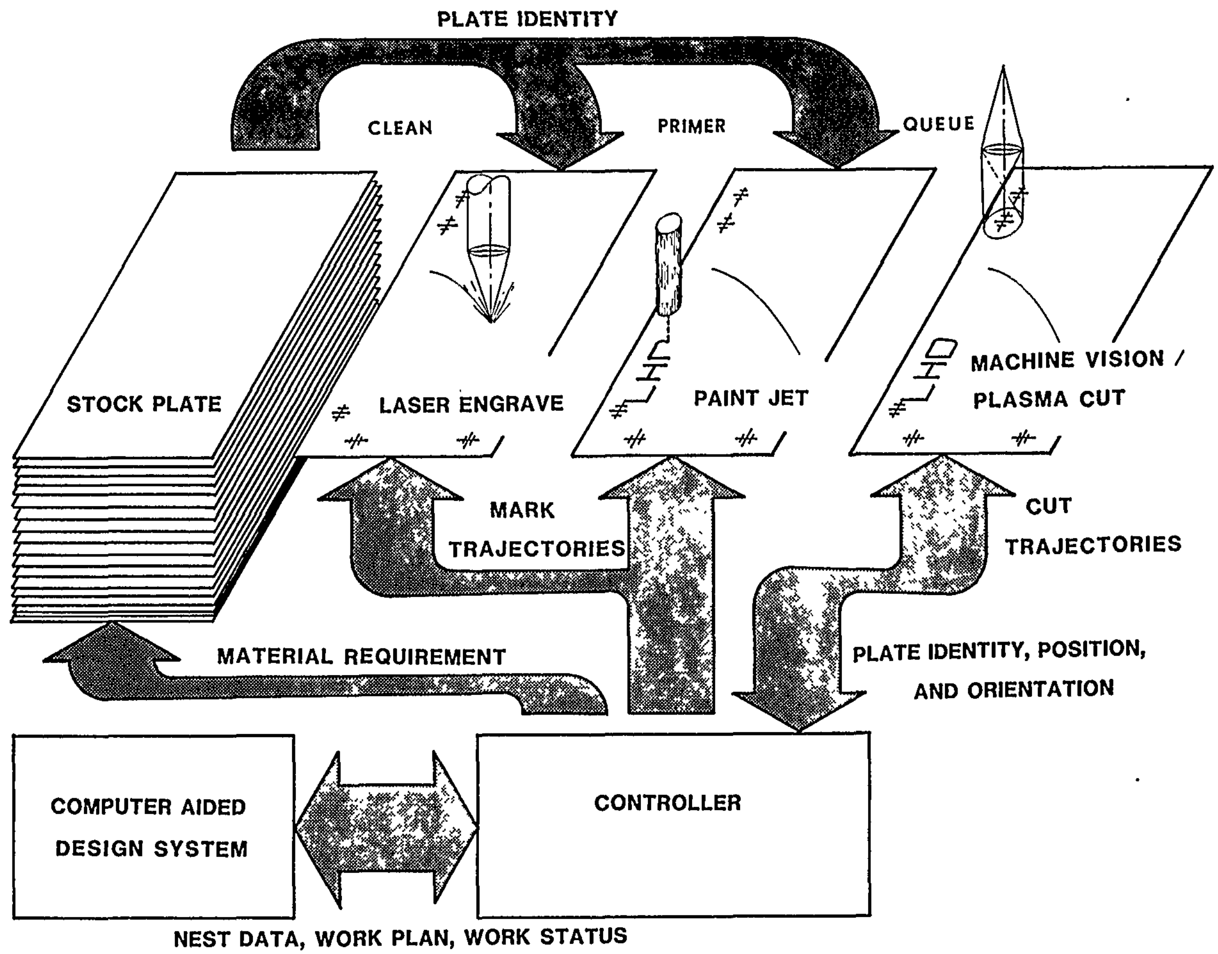

Figure 2. AUTOMARK SYSTEM DESIGN CONCEPT

generate the necessary marking subresource trajectories. These trajectories are shown to accomplish the required marks. Finally, the demonstrations show that the plate edge and the fiducial marks can be sensed by commercially available machine vision subsystems. These data provide adequate information for near real time software alignment between the the plate workpiece and the cut trajectories.

Line Marking Vector Geometry

The capability to create marks in any particular orientation by manipulating a marking resource along a line crossing the direction of workpiece motion is determined by 6 physical parameters. These are the marking speed of the process, S_p, the velocity of workpiece motion, V_p, the marking resource manipulation velocity, V_m, the length of mark required, W_p, the orientation of marking resource manipulation relative to workpiece motion, and the direction of marking resource motion along the manipulation line.

Laser engraving created acceptable marks at maximum marking speeds of at least 300 inches per minute. In order to support the worst case shop load requirement for *total length of plate* per shift, the workpiece velocity is fixed as 180 inches per minute. Commercially available linear stepper motors exhibit maximum rated load velocities of 3000 inches per minute. The most difficult mark to create is a line across the full width of a workpiece. The maximum plate width is 156 inches.

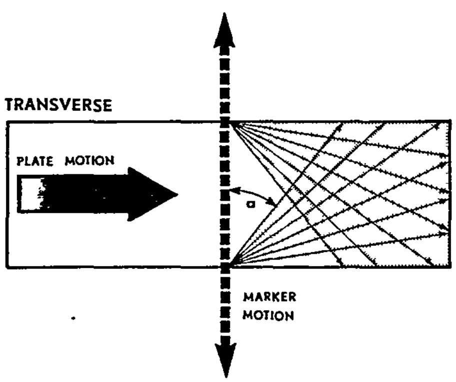

Figure 3. SUPERPOSITION OF POSSIBLE MARK ORIENTATION FAMILIES WITH MARKING RESOURCE MANIPULATION NORMAL TO WORKPIECE MOTION

It is required to create marks at any arbitrary orientation and location on the workpiece surface. It follows that it is requires to create marks at right angles to the direction of workpiece *motion. This cannot be accomplished* by manipulating the marking resource normal to the direction of workpiece motion, since infinite marking speed is not available. To create marks at right angles to the direction of workpiece motion requires marking resource manipulation along a diagonal line. Figure 3, illustrates this fact. The figure shows superposition of mark orientation families possible with marking resource manipulation normal to the direction of workpiece motion. These families occupy mirror image regions. The approach of either region to the workpiece motion direction normal is bounded by equal angles, a. A vector representation of the limiting conditions is shown in Figure 4. Note that the effect of workpiece *velocity*, V_p, is the same as manipulating resource in the opposite direction.

$$a = \text{Sine}^{-1}(|S_m|/|V_p|)$$

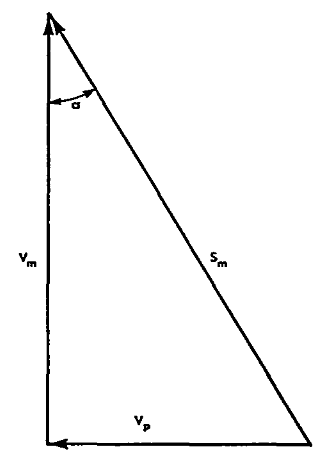

Figure 4. LIMITING MARK ORIENTATION FOR MARKING RESOURCE MANIPULATION NORMAL TO THE DIRECTION OF WORKPIECE MOTION

The angle, d, between the direction of workpiece motion and the direction of the marking resource manipulation line cannot be uniquely determined because only a single fixed value and a pair of maxima are known. The bounds on d can be established. Consider the angle which just satisfies the requirement to mark across the full plate width, W, normal to the direction of workpiece motion. Consider also the angle which *necessitates maximum marking speed* to just achieve the normal to workpiece motion. Figure 5, is a vector representation of these bounding states.

For the state bounded by maximum workpiece plate width,

$$d_1 = \text{Tangent}^{-1}(|W|/|V_p|) = 40.91 \text{ degrees.}$$

For the state bounded by maximum marking speed,

$$d_2 = \text{Tangent}^{-1}(|S_m|/|V_p|) = 590.04 \text{ degrees.}$$

Reversing the direction of marking resource manipulation results in an entirely different condition. This is represented in Figure 6. The angle, e, between the workpiece motion direction and the marking resource manipulation line is the supplement to angle d. The bounds on d apply likewise to e.

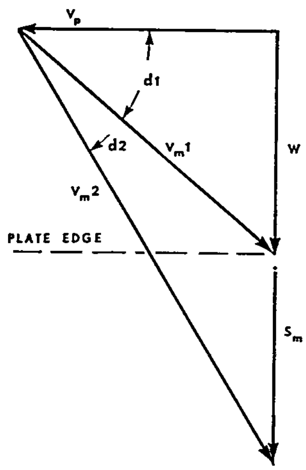

Figure 5. BOUNDING STATES FOR MARKING NORMAL TO THE WORKPIECE MOTION DIRECTION WITH DIAGONAL MARKING RESOURCE MANIPULATION

e_1 = 139.09 degrees.

e_2 = 120.96 degrees.

f is the angle between reverse motion marking resource manipulation and the resulting mark on the workpiece. Using the law of Sines;

$$f = \text{Sine}^{-1}\{(|V_p|/|S_m|)\text{Sine } e\},$$

f_1 = 23.14 degrees,

f_2 = 30.97 degrees.

The angle, g, between the limiting mark orientations and the workpiece motion direction is the difference of d and f.

g_1 = 17.77 degrees

g_2 = 28.07 degrees

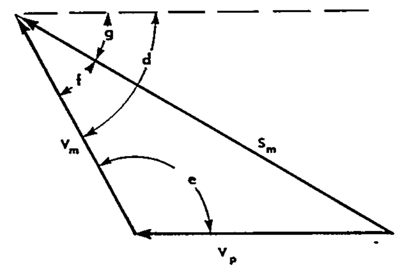

Figure 6. REVERSE DIRECTION DIAGONAL MANIPULATION OF MARKING RESOURCE

Since neither bound permits complete workpiece coverage, a second marking resource is required with manipulation along the opposite diagonal.The arrangement overlaps a second, mirror image, family of possible mark orientations onto the above. This results in complete workpiece coverage. Superposition of the families of possible mark orientations is illustrated on Figure 7.

The sum of workpiece velocity and maximum marking speed are less than maximum marking resource manipulation velocity. In no state is marking resource manipulation velocity a controlling parameter.The length of marking resource maximum traverse associated the workpiece bounded state is 21.37 feet. The length of marking resource maximum traverse associated with the marking speed bounded state is 16.33 feet. AUTOMARK system velocity tolerances and the possible need for retrograde marking orientations must be traded off in the final design with the accuracy and economic implications of the shorter traverse.

<u>Laser Engraving Process Parameter Determination</u>

Tests were accomplished for initial determination of process parameters of laser engraving for a system to automate marking of structural plate. It is anticipated that the work specified will identify potential marking speed and the necessary functional relationships between marking speed, power, pulse rate, and beam delivery to conduct trade-off studies.

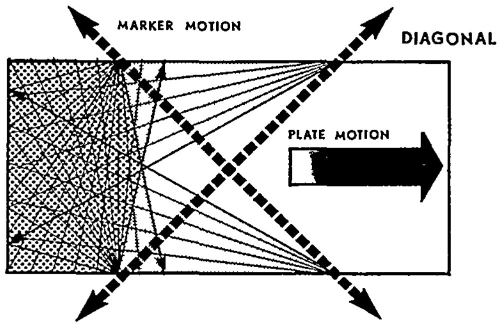

Figure 7. SUPERPOSITION OF FAMILIES OF POSSIBLE MARK ORIENTATIONS WITH DIAGONAL MARKING RESOURCE MANIPULATION

The test coupons were steel plate in a abrasive blast cleaned condition with a surface profile of approximately 0.002 to 0.006 inches. This surface condition is identical with that expected on plate workpieces during system operation. After an initial process parameter estimation, the remaining coupons were marked as follows. The objective mark design required near continuous font with mark width at least equal to depth. A maximum mark width of 0.03 inches was allowed. Mark depth at least 0.008 inches below the effective plate surface and not greater than 0.02 inches was required. The mark design required a rounded bottom contour with a minimum radius approximately equal to mark depth. The minimum allowed speed of advance along a principle direction of line marks is 300 inches per minute.

The effect of process parameter variation on engraving steel plate with a carbon dioxide laser operating in pulsed mode was tested. The effect of process parameter variation was also tested engraving steel plate using carbon dioxide laser operating in continuous wave mode. In continuous wave operation the beam was delivered to the work piece through a final optic such as a boring optic rotating in a small radius about an axis through the line direction of the mark. Alternately some other available means could have been used to generate time variation of continuous wave power delivered to the leading portion of the cut.

Using experience and optional testing as appropriate, a baseline process parameter set with pulsed laser operation and a baseline process parameter set with continuous wave laser operation were determined. Beginning with the baseline process parameter set power was increased over a sequence of intervals. Line mark speed was also increased over a sequence of intervals. Each sequence of intervals formed an approximate exponential series. Each sequence was scaled to permit at least 5 intervals within the capabilities of the equipment.

All parameter combinations from the defined sequences were tested by electing to hold either line marking speed or power constant and varying the other parameter according to the defined sequence along the length of a continuous line trajectory.

Using results of the power and speed functionality tests the power values which exhibited acceptable marking over the widest range of line mark speed were selected. Also, the line mark speed values which exhibited acceptable marking over the widest range of laser power were selected. These parameter combinations were then tested to determine laser engraving process variation with change in beam delivery frequency. Acceptable results were achieved with line marking speeds up to 500 inches per minute.

Using results from all of the previous testing, process parameter sets that exhibited the largest regions of parameter variation that generate acceptable marks were selected. A coupon was positioned such that the surface sloped horizontally with the gradient in a plane parallel to the direction of marking trajectories. Depth of focus tolerance was tested by making a continuous mark along the coupon from a point where the surface was well below the focus to a point where the surface was well above the focus. Machine vision test coupons were marked with a principal line 3.0 inches long. The principal line was crossed with a perpendicular bisector 1.0 inch long such that 0.5 inches of the bisector length lies to either side of the principle line. The principal was also crossed with 2 perpendicular interceptors, 1 to either side of the bisector, spaced 1.0 inch from the bisector. The perpendicular interceptors were be 0.5 inches long such that 0.25 inches of the length of an interceptor lies to either side of the principal line.

Control Feasibility

Copies of typical plate nest images as currently generated for use with a direct computer numerical controlled plasma cutting machine equipped with a pneumatic prick punch marker were used

to demonstrate AUTOMARK system control feasibility. The nest images contained marker trajectories, and associated control data, plasma torch trajectories and associated control data, and high speed traverses separately associated with marking or cutting. The nest images were realized in ESSI notation.

Nest image data was parsed into marking fields and cutting fields. The parsed marking field consisted of a list of marking trajectories. High speed traverses associated with marking trajectories were delimited by the marker control characters. The parsed cutting field contained all nest image data associated with operation of the plasma torch.

Locations and orientations for fiducial marks were programmatically identified according to the rules included in the system requirements. Trajectories for accomplishing the several fiducial marks were programmatically generated and linked to the parsed marking field.

A time domain plan was programmatically evolved for accomplishing line marking spatially distributed over the surface of a plate passing through the marking resource at uniform velocity. The marking resource is partitioned into functionally independent subresources as shown in Figure 8. Marking duty of an individual marking subresource was multiplexed between any number of lines within the physical constraints of the system. Marking duty along any particular line was multiplexed between any number of marking subresources within the physical constraints of subresourse operation defined in the system requirements. The plan allocated marking duty among the marking subresources and defined time domain trajectories along the translational axis of each marking subresource as necessary for accomplishment of the required marks. Plate velocity and motion properties of the marking subresorces was in accordance with the system requirements. The marking duty plan evolved in the following sequence.

Fiducial marks and critical line features such as intersections, stops, and arc segments were identified.

Marking duty assignment and marking subresource trajectories for fiducial marks and critical line feature marks were defined. This assignment accounted for all fiducial mark and critical line feature marking trajectories and traverses of separate marking resources between marking trajectories.

Marking duty assignment and marking subresource trajectories for running line marks were defined. This assignment accounted for running line marking trajectories as well as the maintenance or replacement of fiducial mark and critical line feature mark trajectories. This assignment also accounted for traverses of separate marking subresources between marking trajectories.

Computer graphic display of simulated mark accomplishment was made showing the marking subresource trajectories relative to the plate. The simulation displayed the time domain accumulated result of the several marking subresorces operating simultaneous along the trajectories defined above.

Fiducial Mark Sensing

Laser engraved coupons were coated with approximately 0.001 inches thickness of inorganic zinc primer. These coupons were then used to demonstrate the capability of commercially available machine vision subsystems to image, to programmatically identify the workpiece edge, and to accurately establish the location of these features in the camera field of view. The machine vision subsystems used in these demonstrations were first taught the fiducial mark and the coupon edge features. These programs were then exercised with the coupons placed in differing locations and orientations throughout the camera field of view. The fiducial mark and coupon edge were successfully tracked at frequencies up to 10 Hertz. This frequency is sufficient to support servo controlling camera position from the sensed edge of the workpiece. The frequency is also sufficient to support the equivalent of real time fiducial identification and location in cutting machine coordinates.

PRELIMINARY DESIGN

Evolving a preliminary design simultaneously with preparing system development specifications from the requirements list performs at least three useful functions. The preliminary design serves as an illustrative example of the intent of the specifications and promotes more effective communication between the system designer and potential developers. Evolution of the preliminary design forces careful consideration of conflicts, missing elements, and unrealistic expectations within the specification and encourages resolution. Through the preliminary design, reasonable assurance of system performance levels are gained, and sufficient knowledge of system technical complexity and material requirements are obtained. This knowledge enables computation of reliable system economic justification estimates.

Material Handling Design

The selected AUTOMARK design concept marks plate workpieces while the plates are in motion on a linear conveyor means. For the task of distributing marks over the plate surface, plate motion thus becomes a component of the marking process motion. Very precise real time estimates of the plate location and velocity are necessary to maintain the required line mark geometric fidelity. A test was conducted to measure the components of plate velocity and deflection as the plate was conveyed using the present facility. The roller spacing is 36 inches and nominal conveying speed is 125 feet per minute. Surprisingly little yawing or crabbing motion was observed. Vertical excursions in excess of 2 inches were measured as the leading edge of the plate passed over each succeeding roller. It is necessary to suppress most of this vertical motion in order to establish achievable bounds on the control bandwidth for the laser dynamic focusing mechanism and to preclude collision of the marking tools with the plate. Analysis shows that the vertical motion amplitude is coupled to the conveying speed and very strongly coupled to the conveyor roller spacing. Accordingly, the spacing between full conveyor width rollers is reduced by a third in the preliminary design to 24 inches in the line marking station. In order to further attenuate the amplitude of the plate vertical motion in the marking station, additional short span rollers are positioned between adjacent full conveyor width rollers. Conveying speed is reduced by seven eighths to 15 feet per minute. This conveying speed will just support the worst case plate length shop loading anticipated for the system. This material handling design should result in reducing the vertical motion of the plate to less than 1 per cent of the previous value.

Vertical axis rollers are provided along one edge of the conveyor to establish a physical boundary. Plate workpieces entering the marking station are forced across the conveyor to the boundary rollers. The pusher mechanisms contact workpiece plates with vertical axis rollers. These rollers are isolated from the rest of the pusher mechanism with volute type gas springs to provide a measure of compliance to the actual plate orientation, to suppress impact loading, and to prevent overload of the plate as it achieves alignment with the conveyor edge boundary rollers. Full conveyor with rollers in the marking station are skewed 5 degrees from normal to the conveyor axis to preserve the plate alignment to the boundary rollers achieved by the pusher mechanisms.

Linear arrays of retroflective optical beam breaks are mounted in the gaps between sections of full conveyor width rollers. These sensors provide the AUTOMARK system controller with plate position data and estimates of plate velocity.

Laser Beam Delivery Optics Manipulation

The parameters driving design for delivery of the laser beam to an individual subresource of the line marking station derive from the properties of light transmission and the very large amount of marks to be made. The final delivery optic must be manipulated along linear trajectories up to 30 feet long at velocities as great as 60 inches per second and with acceleration on the order of 50 inches per second squared. The delivery optic is required to dynamically focus on a workpiece with out of plane waves having amplitudes up to 1 inch in thin plate and wave lengths on the order of tens of inches. The required pointing accuracy is on the order of 0.01 inches from true position measured on the plate surface.

Taken together, this means that the laser beam will experience long air passes and be caught by a turning mirror moving along a linear traverse as part of the car carrying the final delivery optic. The dynamics require a compact, very stiff and minimal mass design for the final delivery optic, the car carrying the optic, its attachments and accessory equipment, and any necessary utilities and signal connections. This requirement precludes on car mechanizations of dynamic alignment error compensation and motorized final delivery optic focusing. Focusing will be accomplished with a servo gas cylinder integrated into the design of the barrel of the final delivery optic and powered with excess cover gas or gas from the way bearing supply. Motion of the final delivery optic car is powered by a linear stepper motor for maximum drive response and minimum drive inertia and complexity. The car runs on gas lubricated way bearings for high stiffness and minimal friction. To maintain highly accurate alignment the way bearings are mounted on the sides and the top surfaces of a trapezoid section monocoque beam and grouted into place after final adjustment. Two independent cars operate one on each side of the beam. There are a total of 4 beams supporting 8 final delivery optic cars. The arrangement is shown on Figure 8.

Ink Jet Tool Manipulation

Manipulation of ink jet tools over the surface of workpiece plates to apply alphanumeric character marks is similar

to manipulation of the final delivery optic. The trajectories are linear. High speed manipulation dynamics are required by the large amount of marks to be made. Because ink jet tools can achieve a very high character generation rate, and because the position and orientation tolerances for alphanumeric character location are much broader than for line marks, only 2 ink jet tools are required. These are mounted on separate cars running independently on opposite sides of a single beam across the width of the conveyor. The cars are each driven by linear stepper motors and supported on gas lubricated way bearings. Ink jet tools offer sufficient depth of field for satisfactory process operation so that dynamic compensation for out of plane waves is not required. Adjustment is provided for the various nominal thicknesses of workpiece plate to be marked. The ink jet tools are incapable of rotating characters into alignment with the marking trajectory over the workpiece plate surface. This function is accomplished by a hollow shaft stepper motor which serves as a rotary mounting stage for the ink jet marking tool.

SAFETY CONSIDERATIONS [1]

When high energy density processes are proposed it is essential to question in detail the ability of industry to safely implement the proposal. The AUTOMARK system design concept incorporates a very large laser operating in an environment which cannot feasibly be totally enclosed. Numerous lasers of the proposed type are operational in similar environments throughout the metals working industries. Disabling, and sometimes fatal accidents have happened to personnel working with, or maintaining such lasers. The record shows that these accidents occurred because of disregard of the requirements of law, standard industrial laser practice, or failure to follow other standard industrial practices. Conscientious compliance with the requirements of law Conscientious compliance with the requirements of law and standard industrial practice will result in safe laser use. The Laser Research and Technology Division, Los Alamos National Laboratory, achieved a decade without known permanent biological damage to any of more than 400 personnel working with numerous lasers of various types and wavelengths.

The applicable law is Title 21, Section 1040, Code of Federal Regulations (21CFR1040). The Federal Code references American National Standards Institute (ANSI) Z 136.1 American National Standard For Safe Use Of Lasers as the norm for safe use of lasers in industry. The requirements include a thorough hazard analysis, implementation of engineering controls commensurate with the level of hazard,and institution of management controls to assure compliance.

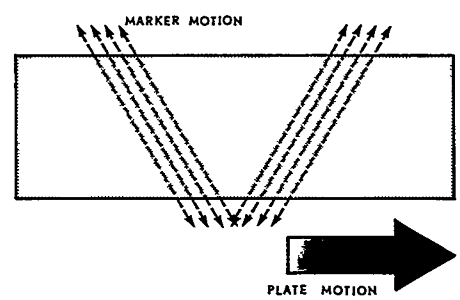

Figure 8. LINE AND FIDUCIAL MARKING STATION RESOURCE ARRANGEMENT

Hazard Analysis

The primary step in analysis of the hazards posed by industrial lasers is to establish the type and class of laser to be implemented, the process to be accomplished, the associated hazard sources, and the probable biological consequences of personnel exposure to these hazards. The AUTOMARK system is proposed using a class 4 pulsed carbon dioxide laser operating with an emissions output power of up to a kilowatt. The laser will emit light with a wave length of 10.4 micrometers. The emissions are within the infrared portion of the electromagnetic spectrum and are not visible. Light from this portion of the spectrum is very heavily attenuated by most glasses and optical grades of plastics. This will permit

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1 This section and associated subsections draw heavily on the requirements and discussion contained in American National Standards Institute (ANSI) Z 136.1-1986 American National Standard For Safe Use Of Lasers. This section and associated subsections are intended as an abstract and analysis of the requirements applicable to AUTOMARK system design and implementation. This section and associated subsections are NOT a substitute for the requirements of law or the American National Standards Institute.

the use of optically clear materials for the necessary process viewing ports and for mandatory use safety glasses.

The optical power of class 4 lasers is sufficient that exposure of personnel to even a portion of the direct beam, and under certain circumstances to diffuse reflections will exceed the maximum permissible exposure.

The maximum permissible exposure has been established for each portion of the electromagnetic spectrum at levels generally a tenth of the damage threshold level for 50 per cent of the general population. These levels show a negligible probability for damage as the result of accidental exposure.

Excessive infrared exposure causes a loss of transparency or produces a surface irregularity in the cornea. The maximum permissible exposure is well below the energy or power required to produce a minimal lesion. A minimal corneal lesion is a small white area involving only the epithelium and whose surface is not elevated or swollen. It appears within about 10 minutes after the exposure. Very little or no staining results from flourescein application. A minimal lesion will heal within 48 hours without visible scarring.

Damage results from the heating of the cornea by absorption of the incident energy by tears and by tissue water in the cornea. The absorption is diffuse, and simple heat flow models appear to be valid. The identity of the sensitive material or protein in the cornea is not known. Although the critical temperature threshold is not known, it does not appear to be much above normal body temperature, and there are indications that it is a function of exposure time.

The large skin surface makes this body tissue readily available to accidental or repeated exposures to laser radiation. The biological significance of irradiation of the skin by lasers operating in the visible and infrared regions is considerably less than exposure of the eye, as the skin damage is usually reparable or reversible. Effects may vary from a mild reddening (erythema) to blisters and charring. Depigmentation, ulceration, and scarring of the skin, and damage to the underlying organs, may occur from extremely high powered laser radiation.

Latent and cumulative effects of laser radiation are not known at this time. The possibility of such effects occurring, however, should not be ignored in planning for personnel safety in laser installations.

The AUTOMARK system design concept permits light tight enclosure of the laser air pass and target workpiece interaction zones. The design concept, however, requires continuous conveying of workpiece plates into and out of the line marking station. Careful engineering controls are required to ensure negligible probability of direct beam or diffuse reflection radiation exceeding the maximum permissible exposure exiting these openings.

Laser cutting and welding operations have been shown to create similar potentially hazardous vapors and fumes as electric arc and flame cutting and welding procedures. The AUTOMARK system line marking station will operate in approximately the same process region as laser cutting. Adequate exhaust ventilation is required to reduce the concentrations of the resultant fumes and vapors to levels below the appropriate threshold. Generally, ventilation adequate for processes using conventional energy sources are also adequate for laser systems accomplishing work at a comparable rate.

Studies have shown that plasma emissions created during a laser welding operation may contain sufficient ultraviolet or blue light content to raise concern for operators viewing a laser welding process long term without additional protection for the plasma emission. The plasma created by the accomplishment of laser engraving of steel plate may contain sufficient ultraviolet or blue light to warrant attenuation of these wave lengths through the process viewing ports.

Operating laser power supplies and discharge tubes are energized to very high potentials and often exhibit considerable capacitance. These circuits pose an electrical shock hazard to maintenance personnel. These circuits should be contained in access interlocked enclosures and provided with bleed down resistors to remove static charges following shut down. Work rule grounding of high voltage parts must be accomplished prior to maintenance. Metallic parts, not intended as current carrying members, should be permanently grounded.

Class 4 laser systems develop sufficient energy densities to serve as ignition sources. It is essential to construct the AUTOMARK system laser enclosure of flame resistant materials.

Safe operation of the AUTOMARK system line marking station requires implementation of a series of engineering hazard controls, and institution of appropriate management controls to assure compliance.

Engineering Hazard Controls

Operation and maintenance of the AUTOMARK system laser will be limited to trained authorized personnel under key control.

The laser will be procured as commercially available equipment embodying standard class 4 laser source safety features. These will include access interlocks and bleed down resistors on high voltage circuits, and explosion containment for the laser tube.

Beam delivery from the laser exit to the subresource distributor will be totally enclosed. It will be provided with a fail safe beam stop capable of absorbing the entire output power of the laser. The beam delivery system will also be provided with a class 1 laser to simulate emissions of the class 4 laser for accomplishing optical alignment.

A long air pass of the direct laser beam is necessary from the distributor to each of the subresource final delivery optics. There also exists significant probability of spectral reflections off facets in the workpiece plate surface. The facets are created as a consequence of abrasive blast cleaning operations. The AUTOMARK system line marking station will be completely enclosed in a room constructed of durable light tight materials such as concrete block. The enclosure room will have a double door for maintenance access. The maintenance access doors will be equipped with panic hardware for emergency exit. Inside the maintenance access doors, a vestibule area will be protected by split overlapped curtains of infrared attenuating plastic. The enclosure room walls will be provided with safety glass process viewing ports. Secondary protection at the process viewing ports will be provided by infrared attenuating plastic curtains hung inside the enclosure room. Metal pass through sleeves will be fitted over the conveyor, at either end of the enclosure room. These sleeves will shield the workpiece plate entrance and exit from the most probable reflections and direct beam paths. Multiply split and overlapped infrared attenuating plastic drags will seal light paths close to the plate surface. Exhaust ventilation will be provided to remove laser engraving process fumes and vapors. The enclosure room doors will be provided with an interlock such that the laser will not operate with the doors ajar. Opening either of the doors during laser operation will result in immediate stopping of the beam and shut down of the laser. Manual restart will be required. Floor mat switch pads located in the enclosure room vestibule and adjacent to the beam distributor and the subresource manipulators will be included in the interlock circuit. Separately hard wired emergency master disconnect switches will be located near the subresource manipulators, in the enclosure room vestibule, on the wall outside the enclosure room doors, and on the operators console. Warning lights and bells will be the first functioning equipment during a laser start evolution. An automatic 2 minute delay will be required, after initiation, to complete a laser start evolution. This delay will allow personnel sufficient time to act to avoid exposure. The bells will be silenced with the beginning of laser beam delivery. The warning lights will continue during laser operation.

The AUTOMARK system will be posted with appropriate advisory and warning signs.

The enclosure room will be provided with permanent lighting, utility electrical power and compressed air, and permanent overhead padeyes for material handling during equipment installation and maintenance.

Management Control of Laser Hazards

A Laser Safety Officer will be designated with the authority and responsibility to monitor and enforce the control of laser hazards, and to effect knowledgeable evaluation and control of laser hazards. He is responsible for hazard evaluation of laser work areas including establishment of the Nominal Hazard Zones. The Laser Safety Officer will recommend and shall approve all laser alignment, operating, and maintenance procedures. He is responsible for assuring that the prescribed control measures are in effect, and shall periodically audit the functionability of the control measures in use. The Laser Safety Officer shall approve the wording on all laser work area signs and equipment labels. He shall approve protective eyewear, clothing, barriers and screens, and shall assure periodic auditing of the proper working order of these items. Prior to initial use of the laser, he shall verify proper installation of equipment or proper restoration of these systems following maintenance. He shall assure that adequate safety education and training are provided to all laser work area personnel. The Laser Safety Officer shall assure the accomplishment of medical surveillance of all laser work area personnel, and cause maintenance of the appropriate records.

Procedures for laser related work will be prepared in consultation with, and approved by the Laser Safety Officer. These procedures will describe in step wise detail the actions to be taken aligning, operating, and maintaining the

AUTOMARK system line marker. Verification signature control will be maintained to assure that all laser work area supervision, operating, and maintenance personnel have read and understood the applicable procedures.

Safety education and training will be provided to all laser work area personnel. The instruction shall assure that all laser work area supervision, operating, and maintenance personnel are knowledgeable of the potential hazards and the control measures for the AUTOMARK system. The instruction will describe the biological effects of laser radiation on the eyes and skin, relation of specular and diffuse reflections and other hazards of lasers including reaction by-products. The AUTOMARK system and the function of the component equipment items will be described. Overall management of laser operations and the responsibilities of individual employees will be explained. Medical surveillance practices for laser work area personnel will be discussed. Training for maintenance personnel and maintenance supervision will include electrical safety practices and cardiopulmonary resuscitation.

Physical fitness assessments are used to determine whether an employee would be at increased or unusual risk in a particular environment. For workers using laser devices, the need for this type of assessment is most likely to be determined by factors other than laser radiation.

Direct biological monitoring of laser radiation is impossible, and practical indirect monitoring through the use of personal dosimeters is not available.

Early detection of biological change or damage presupposes that chronic or subacute effects may result from exposure to a particular agent at levels below that required to produce acute injury. Active intervention must then be possible to arrest further biological damage or to allow recovery from biological effects. Although chronic injury from laser radiation in the ultraviolet, near ultraviolet, blue portion of the visible, and near infrared regions appears to be theoretically possible, risks to workers using laser devices are primarily from accidental acute injuries. Based on risks involved with current uses of laser devices, medical surveillance requirements that should be incorporated into a formal standard appear to be minimal.

Other arguments in favor of performing extensive medical surveillance have been based on the fear that repeated accidents might occur and the workers would not report minimal acute injuries. The low number of injuries that have been reported in the past 20 years and the excellent safety records with laser devices do not provide support to this argument.

Except for examinations following suspected injury, only preassignment medical examinations are required. These examinations establish a baseline against which damage (primarily ocular) can be measured in the event of an accidental injury. The examinations identify certain workers who might be at special risk from chronic exposure to selected continuous wave lasers. Workers medical histories, visual accuity measurement, and selected examination protocols are required. The wave length of laser radiation is the determinant of which protocols are required. Although chronic skin damage from laser radiation has not been reported, and indeed seems unlikely, this area has not been adequately studied. Limited skin examinations are suggested to serve as a baseline until future epidemiological studies indicate whether they are needed or not. Periodic examinations are not required. The primary purpose of termination examinations is for the legal protection of the employer against claims for damage that might occur after an employee leaves a particular job. The decision on whether to offer or require such examinations is left to individual employers.

PRELIMINARY ECONOMIC JUSTIFICATION

Plate currently exits the preparation line into a static queue to await cutting. Cut part shape, size, and the number of identical replications determine the cutting machine destination of each workpiece. The order of plates in the static queue regarding the cutting machine destination of individual workpieces is sometimes quite random and results in considerable shuffling through the queue to reach particular plates.

The majority of plate is cut on either of 2 direct numerical control plasma arc cutting machines. Each machine is provided with a single servo bridge. A pair of servo carriages are mounted on the bridge of each machine. These carriages may be operated singly, with parallel motion to produce identical parts, or with opposing motion to produce mirror image parts. Each of the carriages is provided with a plasma arc cutting torch. Each carriage is also provided with a separately operable pneumatic prick punch marking tool mounted a fixed offset away from the plasma arc torch.

Lines and arcs are drawn as a series of closely spaced punch impressions made

into the workpiece surface. The pneumatic prick punch marker is also capable of creating representations of alphanumeric and any special characters that can be described by a series of line and arc segments.

The tool rate of the pneumatic prick punch is limited by the maximum slew rate of the cutting machine bridges. Since a single marking tool can be engaged with any particular workpiece, mark production is limited by the maximum bridge slew rate. Drawing alphanumeric and special character representations as a series of line and arc segments requires additional time for machinery accelerations at either end of every stroke. Additional traverses to position the marking tool are generally required between productive strokes to draw a particular character, and between adjacent characters. Because of the limited mark production rate, and the inherent inefficiencies of separately drawing characters, the pneumatic prick punch requires an unacceptable amount of time to accomplish character marking. Consequently, the character drawing capability is not used.

Alphanumeric character marking of plate is accomplished by a layout craftsman using a paint tube and referring to a hard copy drawing of the nest to be cut. The craftsman also marks any necessary special characters indicating particular features of the layout and conveying manufacturing instructions.

Manual marking usually proceeds roughly simultaneous with automatic pneumatic prick punch marking of construction and reference lines. The practice is intended to approach transparency of the character marking operation with regard to plate fabrication process lane workpiece productivity. For those cutting nests that include numerous parts, manual character marking is often only partially completed when the automatic marking of lines has finished. Cutting may be delayed until the manual marking is completed. Optionally, manual marking may continue after cutting, during parts pick out. The choice depends upon the press of production schedules and the availability of a second layout craftsman for assignment to the cutting machine. Either way, the unit cost of cut and marked plate parts is increased.

Placing a layout craftsman on a workpiece for manual character marking during automatic line marking involves a small risk of collision of the cutting machine moving parts with the craftsman. Placing the layout craftsman on a workpiece during plasma cutting operations is dangerous. Plasma coolant puddles on the workpiece surface and can cause slipping. Cut parts are held in place primarily by jamming in the kerf. Parts or scrap can spring loose unexpectedly.

Each of the 2 direct numerical control plasma arc cutting machines is provided with a water table platen. The water table platens are each partitioned into 2 separate tanks arranged endwise adjacent. The platen area of each tank is sized for cutting 2 plates 60 feet long by 13 feet wide arranged side by side. Any other arrangement of smaller plates, not exceeding the maximum dimensions of the tank platen, may be accommodated. The endwise arrangement of separated platens permits parts pick out and stock lay down operations to be conducted in one platen partition while workpiece alignment, marking, or cutting operations are accomplished in the adjoining platen partition. This enables plasma arc cutting machine material handling operations that are transparent in regard to plate fabrication process lane workpiece productivity. These material handling operations were carefully observed. They are not included in the economic justification model since under the current arrangement plasma arc cutting machine material handling operations do not determine any component of workpiece productivity.

The support bars in the plasma arc cutting machine platens are spaced sufficiently far apart to create a significant probability of tertiary plate parts falling through the grating. Tertiary plate parts are often required in quantities of multiple tens of identical pieces for a particular structural assembly. Nesting tertiary plate parts on workpieces together with primary and secondary plate parts results in very costly parts sorting and accounting tasks to assure that assembly requirements are met. Consequently, tertiary plate parts are cut using a one to one template following machine to manipulate multiple oxy-fuel cutting torches in parallel. This produces multiple identical plate parts in a single machine pass. The machine is also provided with direct numerical control capability. This eliminates the necessity for a physical template. Stock for tertiary plate parts is drawn from the larger panels dropped in cutting nests of primary and secondary plate parts. Tertiary plate parts are manually laid out with physical templates or working directly on the stock. Alphanumeric and special character marks are manually drawn with a paint tube.

A flame planer is available for simple edge or end trueing and plate squaring operations. A hydraulic shear is used to break plate into bars. Finally, the

plate fabrication process lane is equipped for manual burning operations and manually set track following tractor flame cutting. These secondary methods involve a very large touch labor content for the volume of completed product. Often these methods require production and use of physical templates in support of shop floor work.

Detail shop observations were made of the fabrication of parts from 55 plates cut on the direct numerical control plasma arc cutting machines. The nests were selected as representative of the spectrum for middle sized combatant ships. Drawings of an additional 100 nests were studied to extract such parameters as plate length, length of line marks, number of character marks, length of part edge cut line, and the number of parts per workpiece. The drawing study confirmed that the detailed shop observations are representative of the shipyard work planned for the next decade. Taken altogether the shop observations and the drawing study account for in excess of 2 per cent of the total steel plate part population for LHD 1 class ships.

The maximum plate length fabricated is 60 feet with the mean at 34 feet. The maximum length of line mark required per nest is 1560 feet with the mean at 123 feet. The maximum number of character marks required per nest is 6928 with the mean at 300. The number of character marks required per nest exhibits a significant secondary spike near 2000 characters per nest. The maximum length of part edge cut line is 533 feet with the mean at 167 feet.

Detail observations of the plate fabrication process lane operations and the component tasks performed in accomplishing these operations were made. During these studies it was learned that alignment of plate with the cutting machine occupies 15 to 30 percent of the time that a workpiece is on the platen.

To make maximum use of stock, cutting nests are designed with part edges as close as 0.5 inches from the nominal plate boundaries. Workpieces must be physically aligned with the principal axes of the direct numerical control plasma arc cutting machines. This is necessary to preclude the possibility of a portion of the cut line trajectories from laying outside the plate. Cutting out of the plate boundary produces ragged edges that require rework to repair. Cutting out of the plate boundary can also produce incomplete parts. This generally results in loss of the plate and all prior work on the plate.

Alignment of the plate to the cutting machine is accomplished by the operator positioning the plasma arc torch over a corner of the workpiece and traversing the torch along the plate length to the adjacent corner. From the change in the relative position of the plasma torch and the plate edge, the operator infers any necessary correction. The operator then levers the workpiece in the direction required to achieve alignment. Alignment is retested. This process is repeated until satisfactory alignment is achieved.

Alternately landing workpieces against fixed stops has been considered and rejected. Fixed stops would have to extend approximately 2 inches above the platen in order to adequately align thin plate stock in the warped condition commonly observed. Alignment to stops this high would pose a collision hazard with the plasma torch holder and the workpiece surface sensor unless the cut line limit were redefined 3 inches inside the plate boundary. This level of planned material scrapping is unacceptable to the shipyard.

Simple designs for movable alignment stops have been considered. The movable alignment stops might consist of torque tubes below the platen grate with bearings submerged in plasma coolant. The torque tubes would be provided with stop bars mounted directly to the torque tubes and operating in a lever like manner through the grate. Designs of this class have been rejected for inflexibility to the numerous workpiece arrangements required on the platens. More flexible designs are conceived as mechanically much more complex, costly, and difficult to make reliable. Consequently, highly flexible stop designs have not been considered as viable candidates.

Line marking typically occupies 35 to 50 percent of the time a workpiece is on the direct numerical control plasma arc cutting machine platen. The variation is due to the widely varying amount of line marks required. During the observations, the plasma arc cutting machines incurred 11.2 hours of down time. Roughly half of this down time was attributed to automatic pneumatic prick punch marker related problems.

The AUTOMARK system will reduce the time required to accomplish alignment between the workpiece as landed on the cutting machine platen. Approximately 2 to 2.5 minutes, or about a third of the time of current practice will be required. Time for marking lines or characters with the workpiece on the cutting machine platen will not exist. This will result in the ability to increase workpiece productivity through the plasma arc cutting machines 60 to 100 per cent with

reduced manning. This in turn results in operating fewer shifts to achieve the same work, compressed plate fabrication process lane schedules and more flexible support of erection and outfitting requirements.

Budgetary projections place the cost of the AUTOMARK system installed and ready to initiate production at the order of a million dollars. As with any capital expenditure for manufacturing equipment, the existence of a real and hypothesized work load is required to establish economic justification. Based on plate parts fabrication to support manufacture of ships at a rate equivalent to 40 000 displacement tons per year, the AUTOMARK system should return cost in about 2 years.

CONCLUSIONS

The AUTOMARK system is technically feasible. It will result in marked productivity improvement fabricating plate parts. Development and implementation of the AUTOMARK system can be economically justified.

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